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EFFECT OF DROUGHT, ALUMINUM, AND LOW pH ON GROWTH AND CHEMICAL COMPOSITION OF SUGAR MAPLE SEEDLINGS

R. A. C. PROJECT NO. 271 RR

Report prepared for Environment Ontario by:

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August 1988

JULY 1989

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TABLE OF CONTENTS

ACKNOWLEDGMENTS iii
LIST OF TABLES iv
LIST OF FIGURES vii
LIST OF PLATES xiii

EXECUTIVE SUMMARY 1
RESEARCH RECOMMENDATIONS 3
INTRODUCTION AND RATIONALE 4

PART 1: SYNTHESIS OF THE SOIL,SAND, AND WATER CULTURE EXPERIMENTS 7
PART 2: SOIL EXPERIMENT 17
PART 3: SAND EXPERIMENT 39
PART 4: WATER CULTURE EXPERIMENT 58

PROBLEMS AND SOLUTIONS 88
REFERENCES 95
APPENDIX 101

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LIST OF TABLES

SYNTHESIS OF SOIL/SAND/WATER CULTURE EXPERIMENTS

1-1. Concentrations of elements and selected statistics for sugar maple roots and shoots grown in soil/sand/and water culture experiments. pg. 10

1-2. Concentration of elements in sugar maple shoots compared with healthy and nutrient deficient plants. pg. 13

1-3. Concentration of elements in sugar maple roots compared with healthy and nutrient deficient plants. pg. 14

SOIL EXPERIMENT

2-1. Element concentrations in soil leachates after the soil was subjected to various pH's. pg. 22

2-2. The correlation matrix for element concentrations in shoots versus roots of sugar maple seedlings grown in soil culture. pg. 31

2-3. The correlation matrix for element concentrations in roots of sugar maple seedlings grown in soil culture. pg. 33

2-4. The correlation matrix for element concentrations in shoots of sugar maple seedlings grown in soil culture. pg. 38

SAND EXPERIMENT

3-1. The correlation matrix for element concentrations in roots versus shoots of sugar maple seedlings grown in sponge/sand culture. pg. 44

3-2. The correlation matrix for element concentrations in roots of sugar maple seedlings grown in sponge/sand culture. pg. 54

3-3. The correlation matrix for element concentrations in shoots of sugar maple seedlings grown in sponge/sand culture. pg. 56

SOLUTION CULTURE EXPERIMENT

4-1. Concentrations of elements and molecules inside and outside the dialysis membrane after 48 hours of submergence. pg. 63

4-2. Treatment means of element concentrations with varying polyethyelene glycol concentration, aluminum concentration, and pH for sugar maple seedlings grown in water culture. pg. 69

4-3. Treatment means of element concentrations with varying polyethyelene glycol concentration, aluminum concentration, and pH for sugar maple 2-year olds grown in water culture. pg. 70

4-4. The correlation matrix for element concentrations in roots of sugar maple 2-year olds grown in water culture. pg. 75

4-5. The correlation matrix for element concentrations in stems of sugar maple 2-year olds grown in water culture. pg. 76

4-6. The correlation matrix for element concentrations in stems versus roots of sugar maple 2-year olds grown in water culture. pg. 77

4-7. Treatment means of element concentrations with varying polyethyelene glycol concentration, aluminum concentration, and pH for white spruce seedlings grown in water culture. pg. 81

4-8. The correlation matrix for element concentrations in roots of white spruce seedlings grown in water culture. pg. 83

4-9. The correlation matrix for element concentrations in stems of white spruce seedlings grown in water culture. pg. 85

4-10. The correlation matrix for element concentrations in needles of white spruce seedlings grown in water culture. pg. 86

4-11. The correlation matrix for element concentrations in stems versus roots (a) and needle versus stem (b) of white spruce seedlings grown in water culture. pg. 87

LIST OF FIGURES

SOIL EXPERIMENT

2-1. The effect of varying pH treatment (a,b) and drought treatment (c,d) on the dry weight of roots and shoots (a,c) and the shoot/root ratios (b,d) of sugar maple seedlings grown in soil culture. pg. 25

2-2. The root weight versus the root area (a) and the shoot weight versus the root area (b) of sugar maple seedlings grown in soil culture. pg. 26

2-3. The effect of varying pH treatment (a) and drought treatment (b) on the root and shoot area of sugar maple seedlings grown in soil culture. pg. 27

2-4. The effect of varying pH and drought treatments (C=control, I=intermediate, S=severe) on the concentration of root phosphorous(a), root aluminum (b), and root potassium (c) in sugar maple seedlings grown in soil culture. pg. 29

2-5. The effect of varying pH and drought treatments (C=control, I=intermediate, S=severe) on the concentration of shoot potassium (a) and shoot phosphorous (b) in sugar maple seedlings grown in soil culture. pg. 30

2-6. Root concentrations versus shoot concentrations of phosphorous (a), potassium (b), aluminum (c), and calcium (d) in sugar maple seedlings grown in soil culture. pg. 32

2-7. Root aluminum versus root phosphorous (a) and root aluminum versus root potassium (b) concentrations in sugar maple seedlings grown in soil culture. pg. 34

SAND EXPERIMENT

3-1. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on root aluminum concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture. pg. 42

3-2. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on shoot aluminum concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture. pg. 43

3-3. The effect of varying pH and aluminum treatments on root sodium (a) and shoot sodium (b) concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture. pg. 45

3-4. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on shoot calcium concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture. pg. 47

3-5. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on shoot magnesium concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture. pg. 49

3-6. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on shoot phosphorous concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture. pg. 50

3-7. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on root potassium concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture. pg. 51

3-8. Root concentrations versus shoot concentrations of aluminum (a), sodium (b), and nitrogen(c) in sugar maple seedlings grown in sponge/sand culture. pg. 52

3-9. Root concentrations of aluminum versus magnesium (a), calcium versus magnesium (b), aluminum versus manganese (c), and phosphorous versus nitrogen (d) in sugar maple seedlings grown in sponge/sand culture. pg. 55

3-10. Shoot concentrations of calcium versus magnesium (a) and phosphorous versus nitrogen (b) in sugar maple seedlings grown in sponge/sand culture. pg. 57

SOLUTION CULTURE EXPERIMENT

4-1. The effect of varying pH, aluminum and polyethylene glycol concentration on the percent change in wet weight per day (+/- one standard deviation) of sugar maple seedlings (a) and 2-year olds (b) grown in solution culture. pg. 64

4-2. The effect of varying pH, aluminum and polyethylene glycol concentration on the total dry weight (+/- one standard deviation) in sugar maple seedlings (a) and 2-year olds (b) grown in solution culture. pg. 66

4-3. The effect of varying pH, aluminum and polyethylene glycol concentration on the root aluminum concentration (+/- one standard deviation) in sugar maple seedlings (a) and 2-year olds (b) grown in solution culture. pg. 67

4-4. The effect of varying pH, aluminum and polyethylene glycol concentration on the root calcium concentration (+/- one standard deviation) in sugar maple seedlings (a) and 2-year olds (b) grown in solution culture. pg. 68

4-5. The effect of varying pH, aluminum and polyethylene glycol concentration on the root magnesium concentration (+/- one standard deviation) in sugar maple seedlings (a) and 2-year olds (b) grown in solution culture. pg. 71

4-6. The effect of varying pH, aluminum and polyethylene glycol concentration on the root chloride concentration (+/- one standard deviation) in sugar maple seedlings grown in solution culture. pg. 72

4-7. The effect of varying pH, aluminum and polyethylene glycol concentration on the root sodium concentration (+/- one standard deviation) in sugar maple seedlings grown in solution culture. pg. 73

4-8. Root aluminum versus root iron (a), root chromium (b), and root vanadium (c) in sugar maple 2-year olds grown in solution culture. pg. 78

4-9. The effect of varying pH, aluminum and polyethylene glycol concentration on the root calcium (a), root sodium (b), and root chloride (c) concentrations (+/- one standard deviation) in white spruce seedlings grown in solution culture. pg. 79

4-10. The effect of varying pH, aluminum and polyethylene glycol concentration on the needle aluminum (a), stem aluminum (b), and root aluminum (c) concentrations (+/- one standard deviation) in white spruce seedlings grown in solution culture. pg. 80

4-11. Root aluminum versus root calcium in white spruce seedlings grown in solution culture. pg. 84

LIST OF PLATES

SOIL EXPERIMENT

2-1. Understory vegetation at soil collection site. pg.19
2-2. Typical symptoms of decline in sugar maple. pg.19
2-3. Setup of soil experiment in the Glendon greenhouse. pg.20
2-4. Roots of sugar maple seedlings (a) exposed to Al, and (b) exposed to Al and stained with hematoxylin. Purple areas are locations of Al. pg. 36

SAND EXPERIMENT

3-1. Typical growth of the roots of sugar maple seedlings grown in sponge/sand culture after one month exposure to different Al concentrations. pg. 41

SOLUTION CULTURE EXPERIMENT

4-1. A sugar maple seedling with its root enclosed in a dialysis membrane. pg. 60
4-2. Sugar maple seedlings growing in a growth chamber. pg. 60
4-3. Experimental setup of the nutrient solution experiment in the Mining Building greenhouse. pg. 61
4-4. Pumps circulate the nutrient solution through growth chambers. Styrofoam containers filled with ice packs keep the solution cool. pg. 61

EFFECT OF DROUGHT, ALUMINUM, AND LOW pH ON GROWTH AND CHEMICAL COMPOSITION OF SUGAR MAPLE SEEDLINGS

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EXECUTIVE SUMMARY

1. Chemical composition of sugar maple was a more sensitive indicator of Al, pH, and drought stress than was growth.

2. Sugar maple grown in soils collected from a declining site near Dorset, Ontario, had lower concentrations of nutrients (Ca, Mg, P, K) and higher concentrations of trace metals (Al, Mn) in both roots and shoots than did plants grown in inert media (sand and water culture).

3. Root Al concentrations increased at low pH and at high concentrations of Al in the rooting medium, but did not change appreciably with drought.

4. Some Al was translocated from the roots to the stem but there was little evidence of translocation from stem to leaves in these short (2 week) laboratory bioassays.

5. Root Al concentrations correlated negatively with root Mg concentrations and with root Ca concentrations (sand experiment) which suggest either competitive inhibition or displacement of these cations by Al.

6. There was a significant positive correlation between Al and P in the roots but no significant correlation in the shoots.

7. In the absence of drought, root K concentrations (or K-leakage) may be a useful early warning indicator of Al stress.

8. Sodium concentrations increased in tissue as the concentration in the environment increased and Na was readily translocated from roots to shoots. Similar results were obtained for Cl.

RESEARCH RECOMMENDATIONS

1. Derive more basic knowledge on the biology of sugar maple seed development (i.e. stratification, germination, dormancy, etc.).

2. Derive more information on the cultural requirements of sugar maple seedlings (i.e. moisture, nutrients, temperature, light requirements, etc.).

3. Derive growth and nutrient uptake progression curves used in the commercial production of these seedlings as comparison and reference for tests under greenhouse conditions.

4. Test other techniques (not using PEG) to induce long term drought in seedlings. For instance the Snow and Tingey (1985) plastic chamber system which suspends plant roots above a water column of known length.

5. Test the hypothesis that the chemical composition of forest grown sugar maple seedlings is a good early warning indicator of decline if decline is due to edaphic factors affected by either air pollution or natural processes.

INTRODUCTION AND RATIONALE

Interest in forest decline has reached a new peak with a plethora of publications in both scientific journals and the popular press. Some scientists see similarities between the present decline of sugar maple and past declines of birch and other tree species and believe that it is part of a natural, long-term cycle, typical of our forests (Hornbeck et al. 1986, Johnson and Siccama 1983, Krause et al. 1986). Other scientists, unconvinced that this decline is part of a "natural cycle", are examining effects of climatic extremes and air pollution on forest productivity and tree growth (Hauhs and Wright 1986, Johnson and Siccama 1983, Matzner et al. 1986, Robitaille and Gagnon 1985, Tamm and Hallbacken 1988, Zoettle and Huettle 1986). Journalists link forest decline to acid rain as though this was an accepted fact, although the verdict from the scientific community is not yet in.

Many potential causes are being considered including natural stresses such as drought, frost, insect defoliation, nutrient deficiency; management practices such as vacuum tapping, cattle browsing; and air pollution such as metals, ozone, acid rain as well as its precursors sulphur and nitrogen oxides.

The large areas affected in central Europe and in eastern North America, the number of species showing stress, and the speed with which trees are dying together create a serious problem that is in urgent need of a solution. But before this problem can be solved, the causes of the decline must be determined for each area and for each species.

The purpose of the present report is to examine the combined effects of drought, aluminum, and low pH on the growth and on the chemical composition of sugar maple (*Acer saccharum*) seedlings. Ulrich et al. (1980) hypothesized that these 3 factors interacted and resulted in the decline of European beech in the Solling District of Germany.

We used three rooting media to test our hypothesis: a natural soil collected from a declining site at Dorset, Ontario; an inert medium consisting of sponge and silica sand to allow us to separate the effects of low pH from those of high aluminum; and a water culture containing polyethylene glycol (PEG) as a drought initiator.

We conducted experiments in the greenhouse using sugar maple seedlings and 2-year old plants. The analytical procedures used and the raw data from these studies are provided in the Appendix. What follows are highlights of some of the more interesting results.

The following report is in 4 parts: Part 1 is a synthesis of the experiments conducted in all three rooting media; Part 2 gives an overview of the soil experiment; Part 3 gives an overview of the sponge/sand experiment; and Part 4 gives an overview of the water culture experiment. Some of the problems encountered, their solutions, as well as research recommendations are also included.

PART 1: SYNTHESIS: SOIL/SAND/WATER CULTURE EXPERIMENTS

INTRODUCTION

The effect of low pH, elevated Al, and drought on sugar maple seedlings was tested using three rooting media; a natural soil collected from a site with sugar maple decline, an inert sponge/silica sand combination, and a water culture containing a nutrient solution and polyethylene glycol (PEG) to regulate drought stress.

Soil was selected because it is the most natural rooting media and should most closely mimic field conditions. However it is also the one that is the most difficult to control for soil solution pH, leachable Al, and water potential (drought). The sponge/sand combination allows us to independently control the concentrations of Al and the pH of the rooting media, but once again drought control is difficult. The solution culture, the least natural of the rooting media, allows the roots to grow uninhibited and is ideal for root staining and root biomass measurements. It also enables the best control of solution pH, Al concentrations, and degree of drought. All three rooting media were tested sequentially to overcome the difficulties inherent with each one. A detailed description of each experiment is provided in the following sections (Parts 2 to 4) and in the Appendices (1, 2, 3). What follows is a comparison of the three media and their effect on sugar maple.

RESULTS AND DISCUSSION

Growth

Dry matter productivity proved to be a poor indicator of environmental stress in the early development of sugar maple seedlings. Biomass of roots and shoots were not significantly changed by treatments in any of the three experiments. Lack of growth probably related to the relatively large seed reserves and the pronounced growth determination of this species and to the short duration of the experiment (2 to 4 weeks). A similar lack of growth response was obtained for Douglas-fir, western hemlock, western red cedar, and Sitka spruce (Ryan et al. 1986), when exposed to Al solutions ranging from 0 to 100 mg/L at pH 3.5. On the other hand, studies with sugar maple seedlings in solution culture showed that shoot biomass decreased, while root biomass remained constant at high Al exposure (Thornton et al. 1986)

Our tests with white spruce seedlings (considered less growth determinate than sugar maple), exposed to similar Al and acid stress but a much more severe drought stress over the same response period as that of sugar maple, revealed marked growth inhibition with increasing Al and drought (PEG) regimes. White spruce appears to be moderately resistant to drought but extremely sensitive to Al. Hutchinson et al. (1986) tested the response of 5 conifer seedlings to Al stress. They found that red and white spruce were the most sensitive to Al and that growth was significantly inhibited when the plants were exposed to 5 mg/L Al in 3 month bioassays. Clearly species differ in their relative sensitivity to Al, with some (white spruce) extremely sensitive and other (Douglas-fir) extremely tolerant.

Chemical Concentrations in Roots and Shoots

Plant chemistry was much more sensitive to treatments than plant growth, and the roots were more sensitive to chemical stress than either the stems or the foliage.

Aluminum concentrations were markedly higher in roots than in shoots (Table 1-1). Root Al was consistently elevated when Al availability was increased in the rooting media (i.e. at lower pHs or higher Al concentrations). Concomitant increases in shoot Al were evident only in the sand experiment, demonstrating the relatively slow translocation of this element when compared to Na and Cl which were readily taken up and translocated to the stem and foliage. Truman et al. (1986) reported similar results for Pinus radiata. They found that P and Al were positively correlated in the roots. The total amount of Al taken up by P. radiata was a function of the Al and P concentration in the rooting medium. As solution P concentrations increased, the concentration of Al in the roots increased while those in the shoots decreased. They attributed this to precipitation of Al-P-hydroxy compounds in the root apoplast.

Root Al was also negatively correlated with root K which agrees with findings that K leakage may be a reliable indicator of Al stress in non-drought conditions. Aluminum-tolerant species tend to have

Table 1-1. A comparison of growth and element concentrations in sugar maple seedlings grown in soil, sponge/sand, and solution culture.

EXPERIMENT			N (%)	P (ppm)	K (%)	Ca (%)	Mg (%)	Al (ppm)	Mn (ppm)	Cl (%)	Na (%)	Wt (g)
SOIL	SHOOT	x + s	2.6 + 0.3	650 + 95	0.55 + .07	0.8 + 0.15	0.15 + 0.03	240 + 70	4300 + 800	0.18 + 0.05	nd*	0.23
	ROOT	x + s	2.6 + 0.3	1100 + 190	0.55 + 0.07	0.24 + 0.07	0.09 + 0.03	8000 + 2000	1300 + 200	0.14 + 0.03	0.16 + 0.04	0.11
	S/R ratio		1.0	0.6	1.0	3.3	1.7	0.03	3.3	1.3	nd	2.1
	S vs R corr	r	0.27	0.64*	0.27	0.04	0.27	0.17	0.2	0.09	nd	- -
	SHOOT corr		-Mn	nsc	nsc	+Mg	+Ca	md	- N	nsc	md	- -
	ROOT corr		+Ca	-K -Cl +Al	- P - Al	-Na +N +Mg	nsc	-K +P +Na	nsc	- P	+ Al	- -
	- pH		nse*	- shoot	nse	nse	nse	nse	nse	nse	nse	nse
	+ DRT		nse	- root	+root +shoot	nse	nse	- root	nse	nse	nse	nse
SAND	SHOOT	x + s	1.9 + 0.4	1300 + 300	0.8 + 0.2	1.4 + 0.4	0.27 + 0.06	160 + 130	65 + 25	0.56 + 0.3	0.12 + 0.09	0.1
	ROOT	x + s	1.4 + 0.3	1300 + 400	1.1 + 0.3	0.4 + 0.3	0.27 + 0.09	1300 + 1300	32 + 12	0.7 + 0.2	0.3 + 0.2	0.06
	S/R ratio		1.4	1	0.7	3.4	1.1	0.1	2	0.8	0.4	1.7
	S vs R	r	0.6*	0.4*		0.3	0.4	0.7*	0.4	0.1	0.6*	- -
	SHOOT corr		+ Al,Na,P,Cl - Ca,Mg	+ N,Mn,Cl,Na	nsc	+ Mg,Cl - N,Na	+ Ca,Cl - N,Na	+ N, Mn	+ P,Al,Cl,K	+N,P,Ca, + Mg, Mn	+ N,P - Ca,Mg	- - - -
	ROOT corr		+ P,Na,Al -Ca,Mg	+ N,Na,Al,Mn - Ca	+ Cl	+ Mg - N,P,Al,Mn	+ Ca - N,Na,Al,Mn	+ N,P,Mn -Ca,Mg	+ P, Al - Ca, Mg	+ K, Na	+ N, P, Cl - Mg	- - - -
	- pH		nse	nse	nse	nse	nse	+root +shoot	nse	nse	nse	nse
	+ Al		nse	nse	- root	nse	- root	+root +shoot	+ root	nse	nse	nse
	+ DRT		nse	nse	nse	nse	nse	nse	- shoot	nse	nse	nse
WATER	SHOOT	x + s	nd	1000 + 200	nd	1.1 + 0.2	0.08 + 0.02	300 + 190	94 + 80	nd	nd	0.22
	ROOT	x + s	nd	1800 + 600	nd	0.58 + 0.15	0.14 + 0.04	2800 + 1300	210 + 100	nd	nd	0.11
	S/R ratio		nd	0.53	nd	1.9	0.57	0.11	0.45	nd	nd	2
	S vs R	r	nd	0.38	nd	0.6	0.45	0.58	0.11	nd	nd	– –
	SHOOT corr		nd	nsc	nd	+ Al	nsc	+ Ca	nsc	nd	nd	- -
	ROOT corr		nd	nsc	nd	Mn	+Al,K,Cl,Mn	+ Mg	+Ca,Mg	nd	nd	– –
			nd	-Ca	nd	-Al, -K, -P	-Ca	-Ca	- -	nd	nd	– –
	- pH		nd	nse	nd	-root	nse	+root	nse	nd	nd	nse
	+ Al		nd	nse	nd	-root	nse	+root	nse	nd	nd	nse
	+ DRT		nd	nse	nd	+root	-root	-root	nse	nd	nd	nse

md = missing data
nd = no data
nse = no signficant effect (P<0.05)
nsc = no significant correlation (P<0.01)

* = significant(P<0.01)
- = decrease
+ = increase

a positive correlation between Al and K concentrations as has been shown in *Pinus radiata* (Truman et al. 1986), in the foliage of *Pseudotsuga menziesii, Tsuga heterophylla,* and *Picea sitchensis* (Ryan et al. 1986), and in Al-tolerant varieties of corn and yellow lupin (Guerrier 1978).

Increasing levels of root Al seemed to depress other cations in the roots, such as Mg and Ca in respective sand and water experiments, reflecting either competitive inhibition or displacement of these cations by Al. Similarly concentrations of 0.05 meq Al/L (0.45 mg/L for the trivalent form) in the rooting medium significantly reduced root tissue concentrations of both Ca and Mg in *Pinus radiata* (Truman et al. 1986).

Drought was associated with lower concentrations of P and Al, and with higher concentrations of K in the seedling roots of the soil experiment, and with lower concentrations of root Al and with higher concentrations of root Ca in the water experiment (Table 1-1). The reduced P uptake may be attributed to lower P diffusion with soil moisture stress, while increased cation uptake may reflect maintenance of cation balance due to reduced Al uptake.

Although short term exposure to low pH, elevated Al, and increased drought had no significant effect on growth of sugar maple seedlings, our results show that root chemistry was significantly changed by these treatments, and that root chemistry may be a more sensitive index of early environmental stress in these seedlings than conventional foliar analysis.

Chemical composition of sugar maple differed in the three experiments. Nutrient concentrations of P, K, Ca, and Mg were all lower in the sugar maple seedlings grown in soil than in those grown in sand or water culture (Tables 1-2 and 1-3). All four of these nutrients have been shown by foliar analysis and fertilizer experiments to be limiting in areas where sugar maple is showing symptoms of decline (Hutchinson, pers. comm.). Also there seems to be considerable heterogeneity in soil fertility and chemistry by site or region. For example, K deficiency seems to be a more serious problem in sugar maple growing in Quebec soils than in Ontario soils. Interestingly, tissue concentrations of the same nutrients (Ca, Mg, P, and K) were also reduced at high concentrations of Al (>1000 µM or 27 µg/L) in laboratory bioassays (Thornton et al. 1986).

It should be noted that the soil used in the present experiment came from a site where approximately 25% of the mature sugar maple showed obvious decline symptoms. This soil was collected beneath both healthy and dying trees to give a "representative soil" for this site. Studies by Kinch and Hutchinson (pers. comm.) and by Hutchinson and Adams (pers. comm.) clearly indicate that soils differ in their nutrient status beneath healthy trees and dying trees. It is possible that our results are picking up an early indication of nutrient deficiency at this site relating to soil acidification and Al leaching or the naturally low fertility of the soil.

Table 1-2. A comparison of element concentrations in shoots of sugar maple seedlings grown in soil, sponge/sand, and water culture, and reference concentrations for healthy and deficient sugar maple seedlings.

					REFERENCE VALUES*	
ELEMENT	(units)	SOIL	SAND	WATER	HEALTHY	DEFICIENT
N	%	2.6	1.9	nd	1.7-2.2	<0.9-1.6
P	ppm	650	1300	1000	800-2000	<500-600
K	%	0.55	0.8	nd	0.57-0.9	<0.23
Ca	%	0.8	1.4	1.1	0.26-2.9	<0.86
Mg	%	0.15	0.27	0.08	0.1-0.4	<0.09
Al	ppm	240	160	300	83	- -
Mn	ppm	4300	65	94	19-1500	- -
biomass	g	0.23	0.1	0.22	- -	- -
age	months	1	1	24	- -	- -
dur exp	days	28	28	14	- -	- -

REFERENCES* = Chandler 1939; Crum & Franzmeier 1980; Erdmann et al. 1979; Henry 1973; Leaf 1973; Stone 1968.

biomass = dry weight at end of experiment

age = age at beginning of experiment

Table 1-3. A comparison of element concentrations in roots of sugar maple seedlings grown in soil, sponge/sand, and water culture, and reference concentrations for healthy and deficient sugar maple seedlings.

ELEMENT	(units)	SOIL	SAND	WATER	REFERENCE VALUES*	
					HEALTHY	DEFICIENT
N	%	2.6	1.4	nd	1.8	1.2
P	ppm	1100	1300	1800	2400	700
K	%	0.55	1.1	nd	0.94	0.34
Ca	%	0.24	0.4	0.58	0.76	0.1
Mg	%	0.09	0.27	0.14	0.3	0.07
Al	ppm	8000	1300	2800	188	- -
Mn	ppm	1300	32	210	8.5	- -
biomass	g	0.11	0.06	0.11	- -	- -
age	months	1	1	24	- -	- -
dur exp	days	28	28	14	- -	- -

REFERENCES* = Chandler 1939; Crum & Franzmeier 1980; Erdmann et al. 1979; Henry 1973; Leaf 1973; Stone 1968.

biomass = dry weight at end of experiment

age = age at beginning of experiment

These conclusions are in general agreement with published results for healthy and deficient sugar maple seedlings in pot experiments (Chandler 1939, Stone 1968, Henry 1973, Leaf 1973, Erdmann et al. 1979, Crum and Franzmeier 1980). Concentrations of P and Ca in the shoots are within the deficient range, while those for K and Mg are at the lower end of the range for healthy sugar maple seedlings (Table 1-2). Similar trends are apparent in the roots (Table 1-3). One qualification we should make is that the plants compared in Tables 1-2 and 1-3 differ in age, size, and experimental exposure. Since we cannot quantify the effects of these factors on plant chemical status our conclusions are tentative and need to be further tested.

In contrast to macro nutrients, concentrations of Al and Mn were both elevated in the sugar maple grown in soil as compared with those grown in the sand/water culture (Table 1-2). Aluminum in the roots was 3 to 6 times higher in the soil experiment than in the water culture, while Mn was 3 to 400 times higher. Metals (Al, Fe, Mn, Zn, Cu etc.) become more soluble and more bioavailable at low pH (Dickson 1978, Hutchinson 1980). All but Al are essential to plant growth. Concentrations of Mn are much higher than in healthy sugar maple seedlings. Whether these concentrations are deleterious for growth and for the normal development of these seedlings remains to be determined.

These results are consistent with other studies (Hutchinson and Adams, pers. comm.; Kinch and Hutchinson, pers. comm.) which have shown nutrient limitations and elevated Al in seedlings grown in soil collected beneath dying sugar maple trees. We also found elevated Mn which is consistent with the soil acidification hypothesis.

If decline relates to soil chemistry then the chemical composition (i.e. lower concentrations of Ca, Mg, P, and K, and higher concentrations of Al and Mn) of sugar maple seedlings grown in field soil in laboratory bioassays may be a good early warning indicator of decline. It is also possible that the chemical composition of sugar maple seedlings growing in the forest at a declining site may provide one of the more sensitive responses to stress. We know that the upper soil horizon receives direct wet and dry deposition of airborne pollutants and is also the layer in which seedlings geminate. This interface is potentially vulnerable to airborne pollutants.

Concentrations of N were much lower in the sugar maple grown in the sand and water culture experiments than in the soil experiment and in some of the reference experiments (Tables 1-2, 1-3). If we assume that the N in the soil was ideal for sugar maple growth, these results may indicate a N-limitation in the Ingestad nutrient medium we used, which was originally intended for birch. Clearly to do experiments of this nature we need to know the optimum conditions for the growth of sugar maple.

PART 2: SOIL EXPERIMENT

INTRODUCTION

The purpose of this experiment was to determine the effects of acidic "rain" on the growth and on the chemical composition of both roots and shoots of sugar maple. The "rain" was applied directly to the soil and in that sense differs from rain falling onto the leaves of plants. We were particularly interested in determining the effects of this acid rain on the mobilization of aluminum from the soil and its subsequent effects on seedling growth and nutrient content.

Site Description

Soils were collected from the Ontario Ministry of Natural Resources stand 173/231, 25 km south of Dorset, Ontario. The soil at this site is a humic gleysol. The Ah horizon at 10 to 25 cm depth contains 29% organic matter, has a pH of 4.85, a CEC of 46 meq/100 g, and the following concentrations of extractable nutrients: K 0.47, Ca 4.72, and Mg 0.87 meq and P 2.29 mg per 100 g dried soil. The soil is derived from a sandy loan parent material (C horizon) of pH 5.25.

Vegetation at this site consists primarily of sugar maple (Acer saccharum), although iron wood (Ostrya virginiana), hazel (Corylus cornula), yellow birch (Betula alleghaniensis), beech (Fagus grandifolia), red maple (Acer rubrum), white and red ash (Fraxinus americana and F. pennsylvanica) as well as balsam fir (Abies balsamea) and hemlock (Tsuga canadensis) are also present. The understory vegetation is typical of a mixed forest with clubmoss, grasses, sedges, mint and violets (Plate 2-1).

A significant number of the sugar maples at this site are showing symptoms of decline. These symptoms include small leaves, premature fall colors, and thinning of the crown (Plates 2-2). This site is neither managed nor tapped, it is located sufficiently far from roads to exclude the possible effects of oil and road salt, and has had no obvious insect infestations for the past 10 years. The cause of sugar maple decline at this site is not known.

METHOD

Sugar maple seedlings for this experiment were collected in 1984 from Denbigh, Ontario (north-east of Dorset) by the Canadian Forestry Services National Tree Seed Center in Petawawa. Seedlings were approximately one month old at the start of the experiment. Treatments to which the seedlings were exposed include three moisture regimes (control, intermediate, severe drought), and 4 pHs (5.5, 4.5, 3.5, 2.5) (Plate 2-3). Methods of drought control and pH adjustments are provided in Appendix 1. A total of 144 seedlings were used in this experiment with 12 seedlings per treatment.

Seedlings were harvested after 4 weeks. Final root and shoot weight and area were determined as were the concentrations of Al, Mn, Ca, Mg, Cl, Na, K, P and total N in both the roots and shoots. Refer to Appendix 1 for methodology and Appendix 4 for raw data.

Plate 2-1. The understory vegetation at the soil collection site.

Plate 2-2. Typical symptoms of decline in sugar maple.

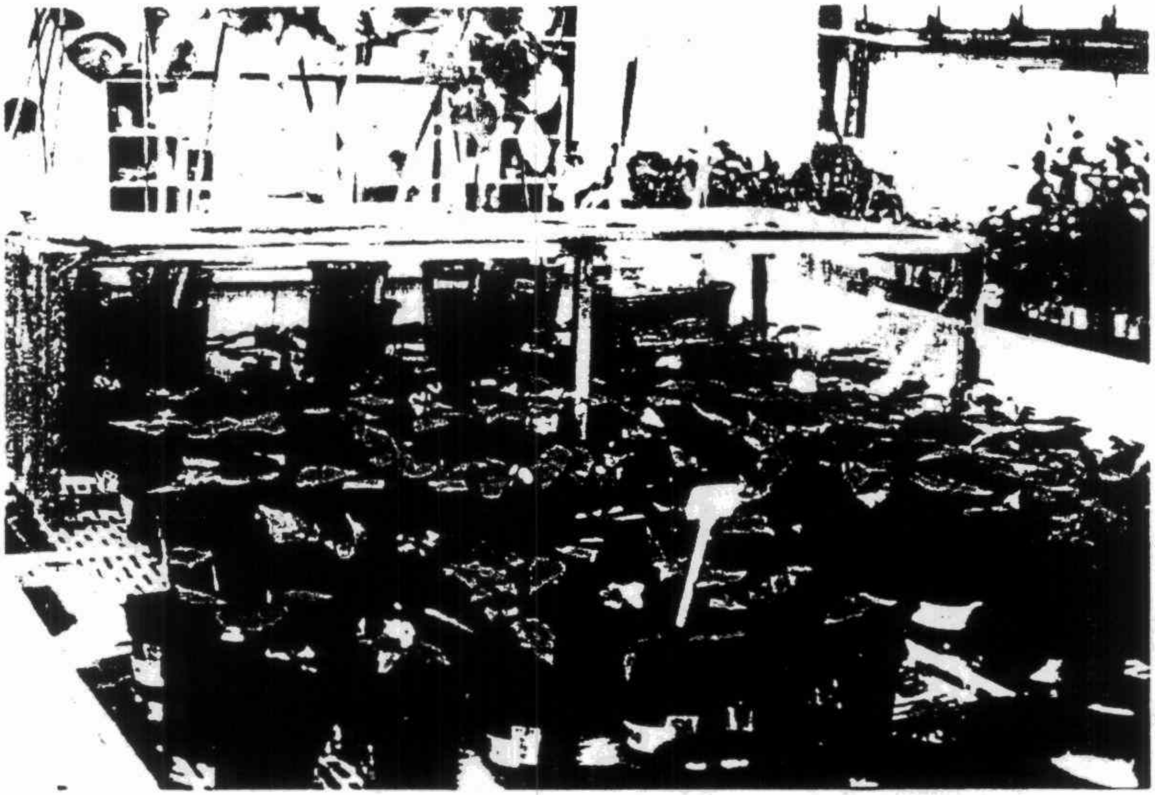


Plate 2-3. The set-up for growing sugar maple seedlings in soil culture in the Glendon Hall Laboratory.

RESULTS AND DISCUSSION

Seeds

For the past three or four years the percentage of viable seeds produced by sugar maple has been quite low. Consequently, obtaining sufficient quantities of viable seeds for our experiments has not been easy. A decrease in seed production is known to happen periodically and tends to last for one, two, and occasionally for three consecutive years. If seed production remains below normal this coming year it will be a most unusual event with four consecutive years of low viability. The factors causing reduced viability are poorly understood. It is possible that the same factors may be contributing to both tree decline and reduced seed production. Cox (pers. comm.) found that air pollution decreases successful pollination in several species including sugar maple.

Effects of pH on Soil Leachate Chemistry

Low pH is known to release metals from soil. Soil samples were leached continuously for 24 hrs with the treatment solutions. Even in this rather short-term experiment metals were released at the lowest pH (pH 2.5). Aluminum concentrations increased from a reference value of 1.0 to 1.8 ppm, Mn from 1.1 to 9.2 ppm, Ca from 0.3 to 1.3 ppm, Mg from 0.1 to 0.4 ppm, and K from 0.3 to 0.5 ppm. Of the 6 elements tested, only P did not increase in concentration at low pH (Table 2-1).

Table 2-1. Element concentrations in soil leachates after the soil was subjected to various pH's.

TREATMENT	ELEMENT CONCENTRATION (mg/L)					
pH	Al	Mn	P	K	Ca	Mg
5.5	1.04	1.11	0.61	0.30	0.33	0.11
4.5	1.19	1.94	0.74	0.34	0.29	0.11
3.5	0.75	1.89	0.44	0.40	0.40	0.14
2.5	1.76	9.23	0.64	0.54	1.33	0.39

Due to the short duration of this experiment and the moderate buffering capacity of the soil, soil pH did not change appreciably from the original pH 4.85. While soils can and do acidify as a result of acidic deposition (Tamm and Hallbacken 1988) the time is measured in years rather than weeks as in most laboratory experiments. Consequently although the soils were watered with different pH solutions, they buffered these solutions to give similar final pHs. Interpretation of the results becomes more difficult since we do not know the range of pHs to which plant roots were exposed. If soils are poorly buffered or if an inert medium is used (as in the following two experiments) the effects of pH can be determined more readily. However, this experiment is more natural since the roots of plants growing in the field are also exposed to rain which has been buffered by the soil.

While the soil used in this experiment was acidic, a pH of 4.85 is not considered to be excessively acidic to inhibit growth of most tree species. Aluminum is readily leached from soils at low pH, however pHs below 4.3 are more conducive to Al leaching than higher pHs. This explains the rather low Al concentration in the acidic leachate (1.0 ppm at pH 5.5 vs 1.8 ppm at pH 2.5). Leachate Al concentrations in the field can exceed 50 ppm and occasionally 100 ppm provided that the soil is acidified (Hutchinson 1980). Based on soil and leachate chemistry, this soil is moderately well buffered and is unlikely to be extremely sensitive to acidification. Plants growing in this soil are also likely to be better buffered against extremes in either pH or Al concentrations than plants growing in more acidic and poorly buffered soils.

Plant Biomass

Root and shoot biomass is not a sensitive parameters in one month old seedlings. Sugar maple appears to have a determinant growth pattern that is insensitive to environmental vagaries (Kuja, pers. comm.). Therefore biomass (or growth) of sugar maple seedlings is a poor early warning indicator of environmental stress. The only statistically ($P<0.05$) significant results were a slight (10 to 20% of control) increase in the shoot to root ratio at low pH and a slight decrease at severe drought (Fig. 2-1). These were due to a decrease in root weight at low pH and of shoot weight at increasing drought. A 10% reduction in biomass within 4 weeks may be significant when extrapolated to an entire growing season of 3 to 4 months.

Root and shoot area may be more useful measurements physiologically since one heavy fibrous root is less effective at obtaining water and nutrients than several light feeder roots but they are also more difficult to measure. In the present study the relationship between weight and area was moderately good with an R-squared value of 0.38 and 0.59 for roots and shoots respectively (Fig. 2-2). No significant effect on root or shoot area was observed (Fig. 2-3).

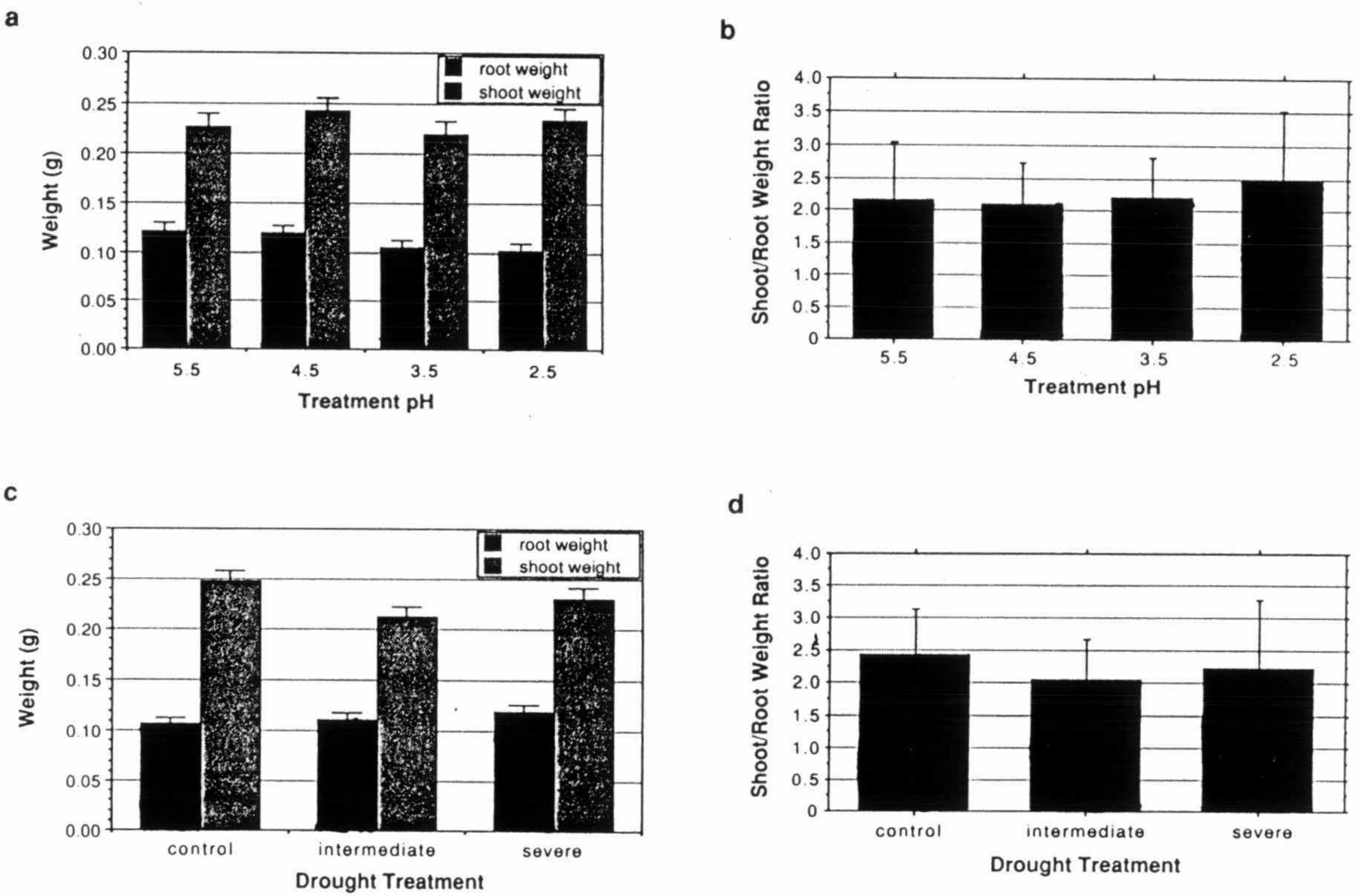


Figure 2-1. The effect of varying pH treatment (a,b) and drought treatment (c,d) on the dry weight of roots and shoots (a,c) and the shoot/root ratios (b,d) (+/- one standard deviation) of sugar maple seedlings grown in soil culture.

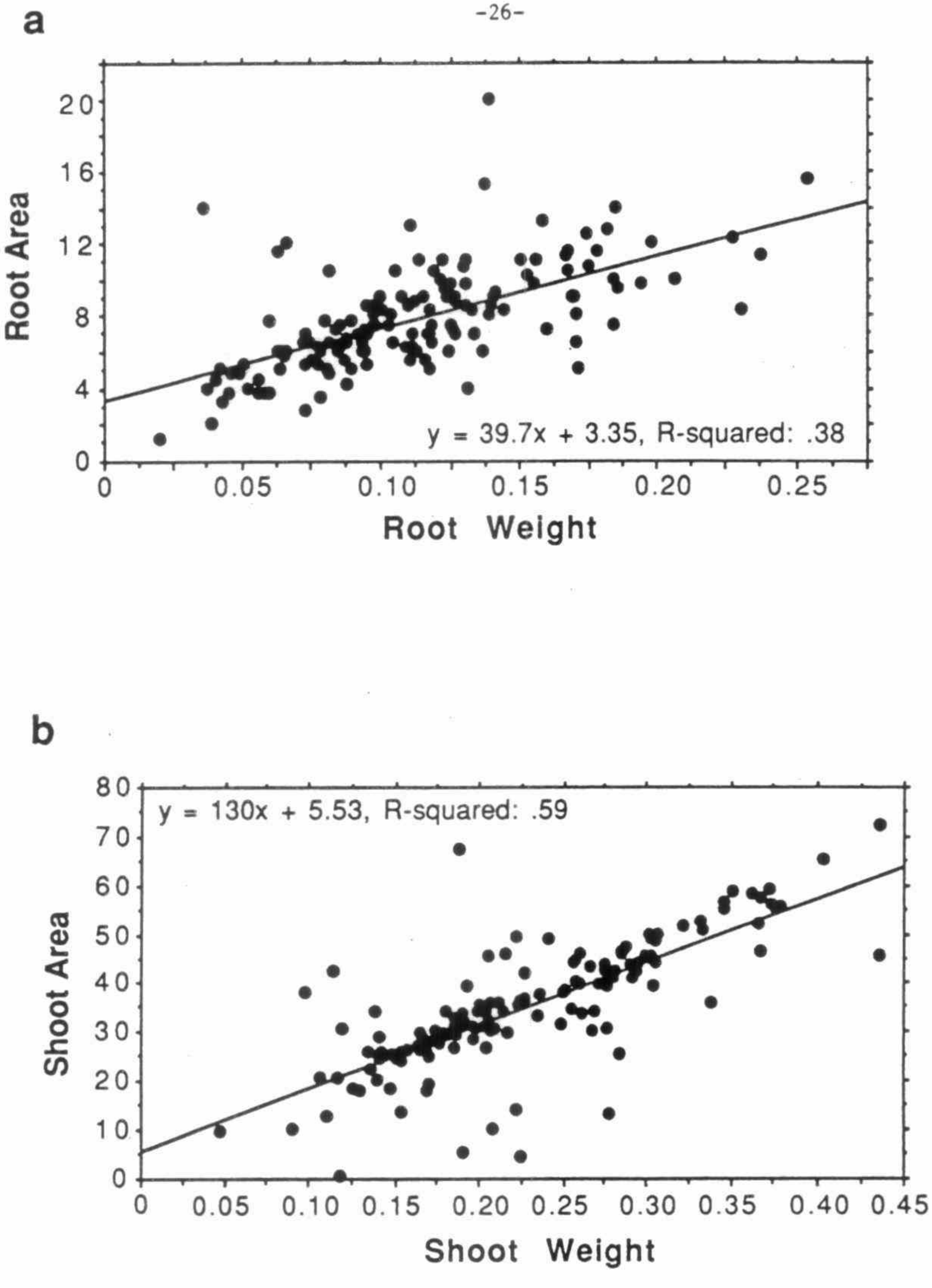


Figure 2-2. The root weight versus the root area (a) and the shoot weight versus the root area (b) of sugar maple seedlings grown in soil culture.

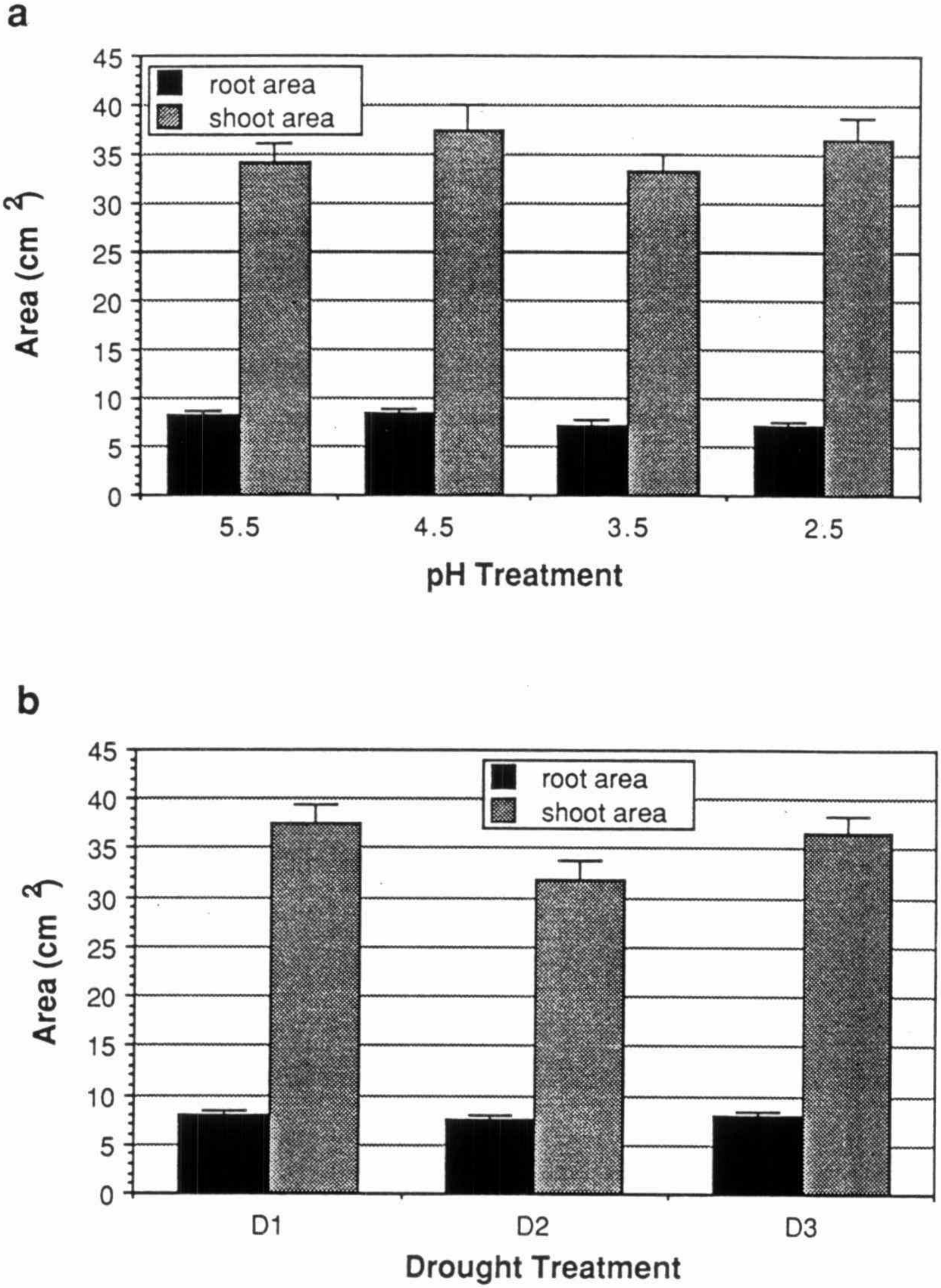


Figure 2-3. The effect of varying pH treatment (a) and drought treatment (b) on the root and shoot area (+/- one standard deviation) of sugar maple seedlings grown in soil culture.

Plant Chemistry

Plant chemistry was much more sensitive to the treatments than was plant biomass. Increasing drought was associated with lower concentrations of P and Al and with higher concentrations of K in the roots (Fig. 2-4). This higher concentration of K was also reflected in the shoots. Lower pHs (pH 4.5 and 3.5) were associated with lower P concentrations in the shoots (Fig. 2-5). pH had no additional effect on either root or shoot chemistry.

Sugar maple seedlings are highly variable chemically with standard errors averaging approximately 10 to 20%. Consequently more replicates than was used in this experiment would be preferable.

The relationship between root and shoot P was significant ($P \leq 0.01$) with an R-squared value of 0.414 (Table 2-2, Fig. 2-6a). None of the other elements were significantly correlated in the roots and shoots (Figs. 2-6 b-d).

Concentrations of Al in the roots were 30 times higher than in the shoots (Fig. 2-6 c). Some of this root Al may have been contamination from adhering soil particles since the values were much higher in this experiment than in the following two experiments (Table 1-3).

Root Al was positively correlated with root P (Table 2-3, Fig. 2-7 a). Aluminum is known to bind with P in the form of ortho-phosphate (Foy 1974). Aluminum can bind to the P inside or outside of the

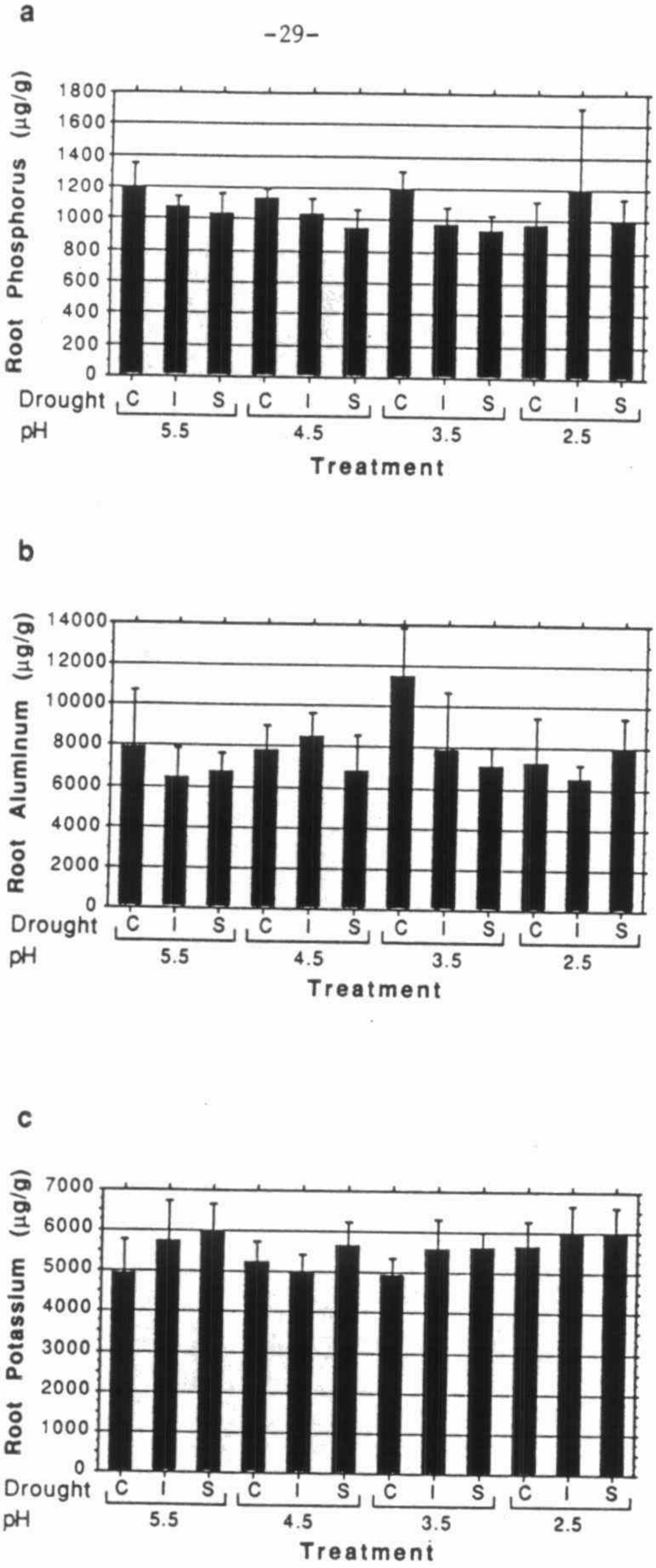


Figure 2-4. The effect of varying pH and drought treatments (C=control, I=intermediate, S=severe) on the concentration of root phosphorous(a), root aluminum (b), and root potassium (c) (+/- one standard deviation) in sugar maple seedlings grown in soil culture.

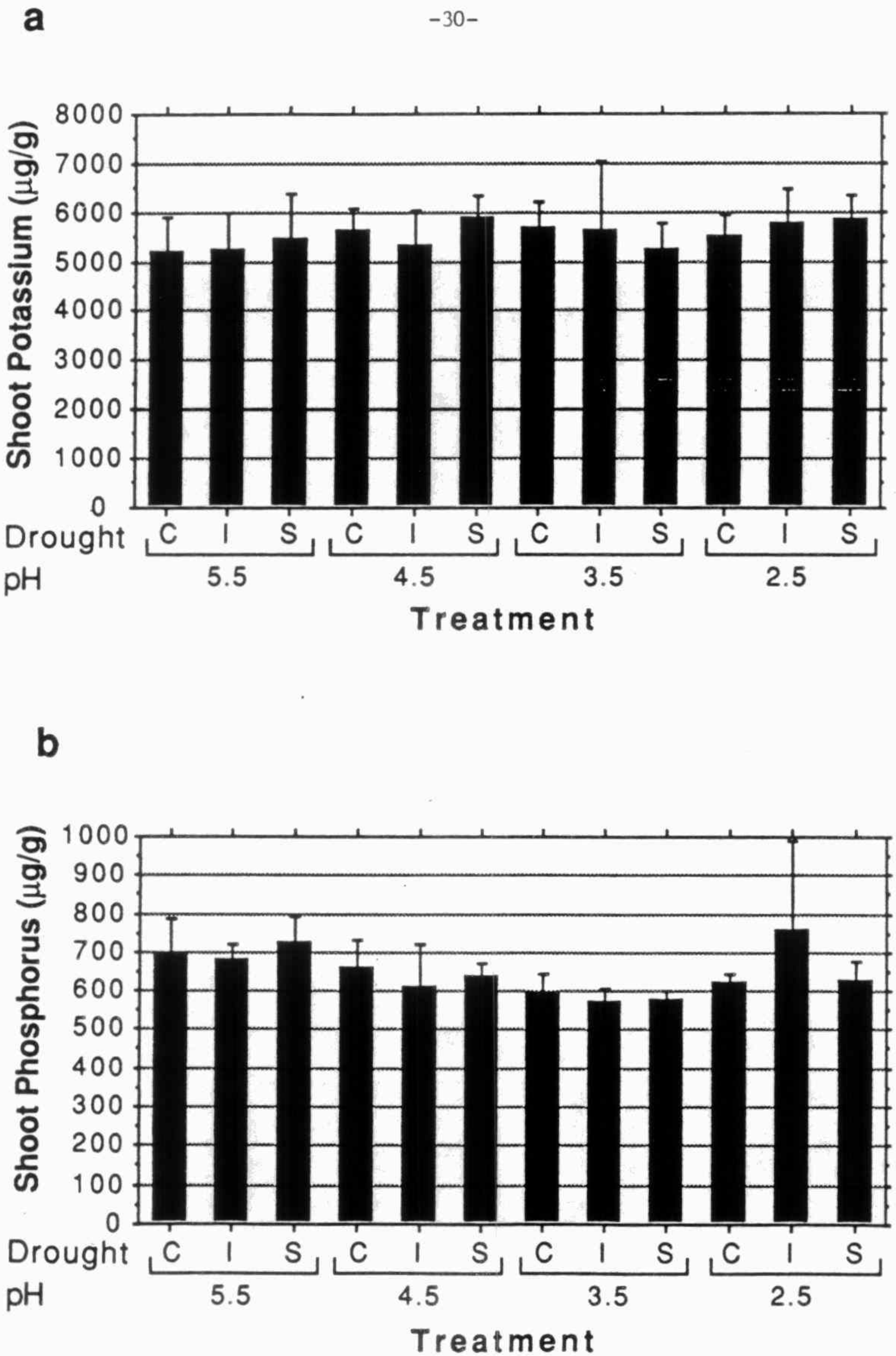


Figure 2-5. The effect of varying pH and drought treatments (C=control, I=intermediate, S=severe) on the concentration of shoot potassium (a) and shoot phosphorous (b) (+/- one standard deviation) in sugar maple seedlings grown in soil culture.

Table 2-2. The coorelation matrix for element concentrations in shoots versus roots of sugar maple seedlings grown in soil culture.

ELEMENT	COUNT	CORRELATION	R-SQUARED	SIGNIFICANCE
Al	44	0.173	0.030	NS
Ca	32	0.041	0.002	NS
Cl	47	0.092	0.008	NS
K	48	0.273	0.075	NS
Mg	48	0.269	0.072	NS
Mn	46	0.200	0.040	NS
N	48	0.269	0.073	NS
P	48	0.643	0.414	0.01

(NS=not significant)

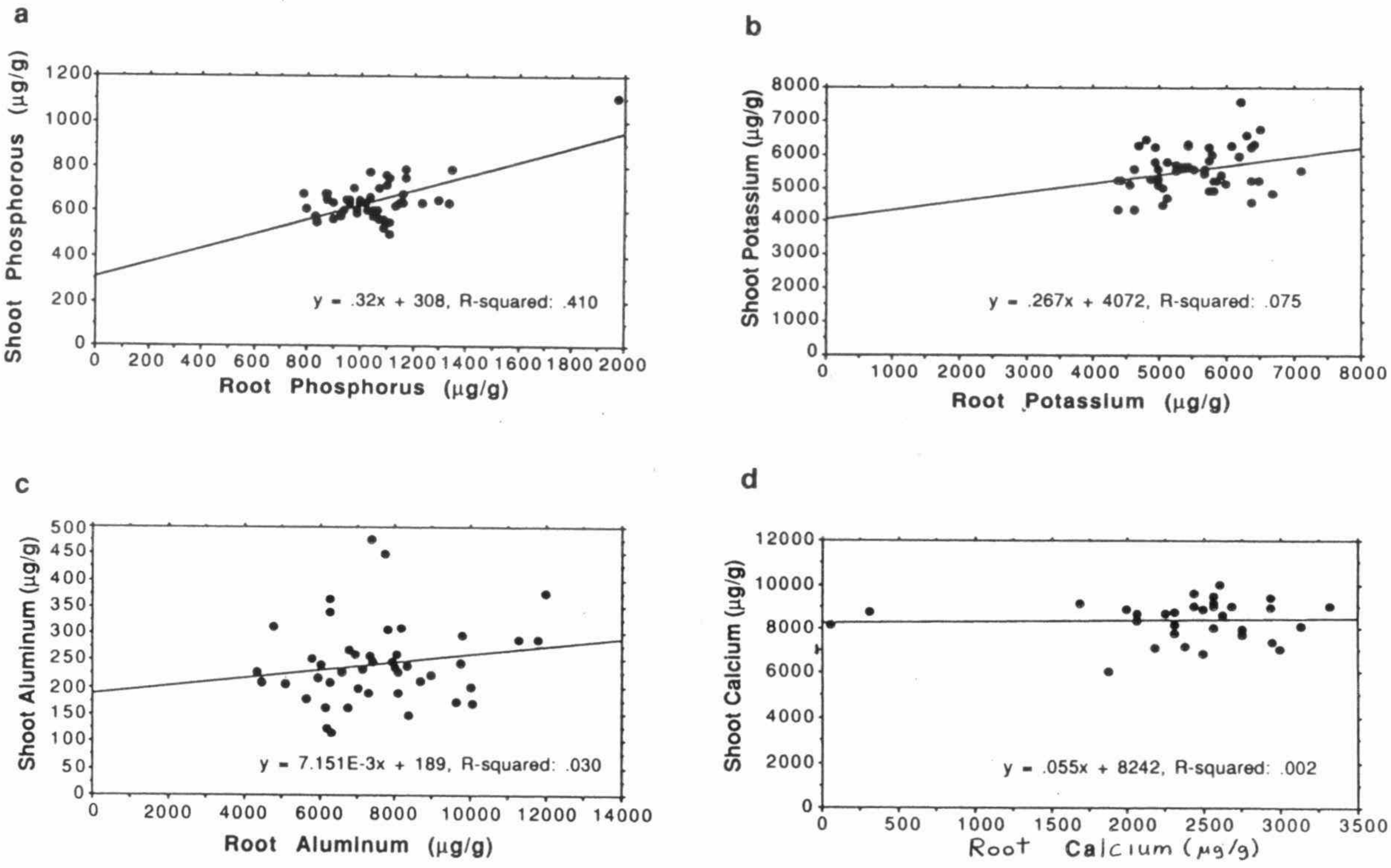


Figure 2-6. Root concentrations versus shoot concentrations of phosphorous (a), potassium (b), aluminum (c), and calcium (d) in sugar maple seedlings grown in soil culture.

Table 2-3. The coorelation matrix for element concentrations in roots of sugar maple seedlings grown in soil culture.

	Al	Cl	K	Mg	Mn	N	Na	P
Al	1							
Cl	-.299	1						
K	-.394	.137	1					
Mg	-.285	.205	.346	1				
Mn	.259	-.217	.361	.176	1			
N	.055	-.034	.134	.169	.085	1		
Na	.503	.054	-.009	-.161	.311	-.028	1	
P	.617	-.437	-.456	-.07	.162	.074	.338	1

N=47

FOR SIGNIFICANCE=0.05, R>= 0.288

FOR SIGNIFICANCE=0.01, R>= 0.372

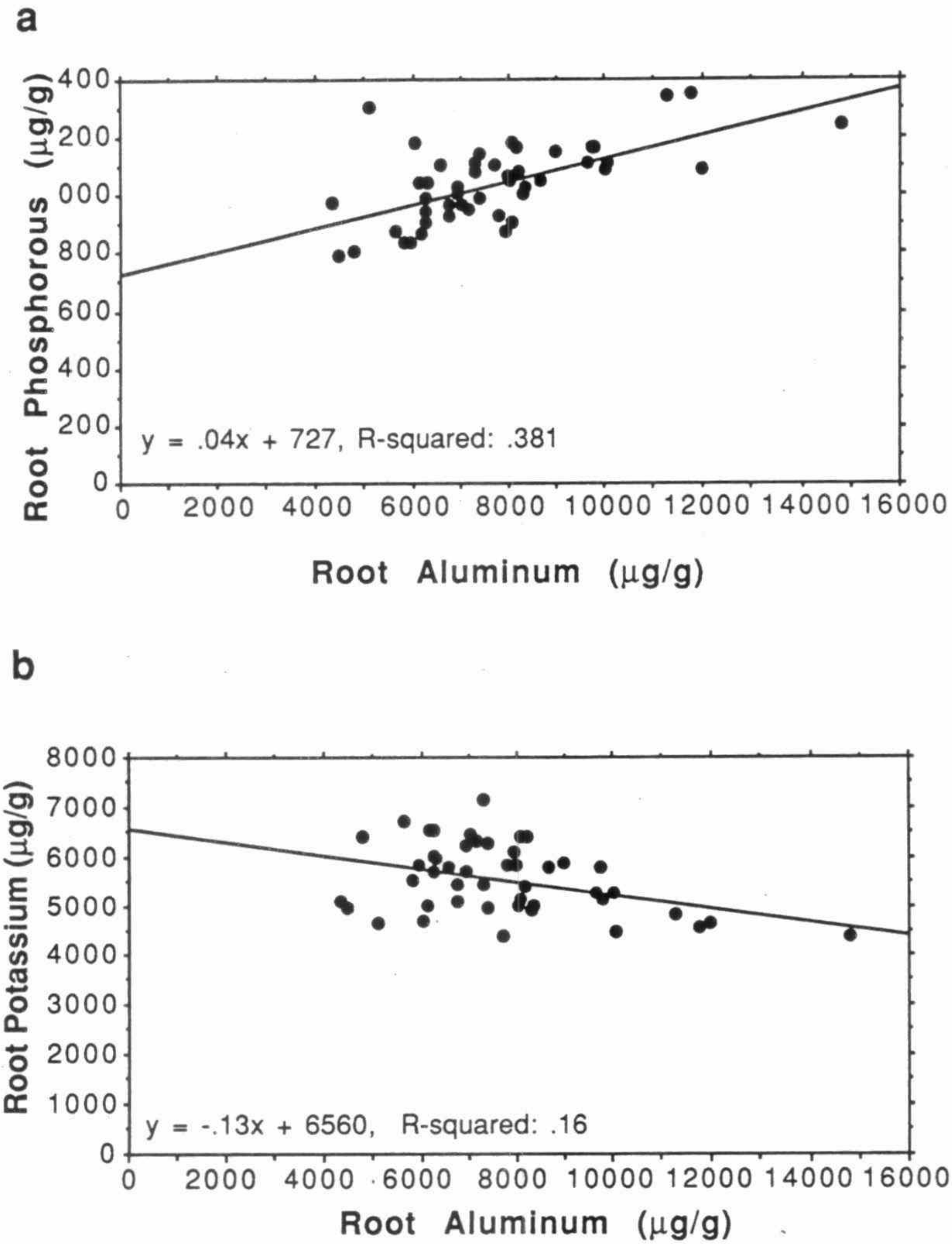


Figure 2-7. Root aluminum versus root phosphorous (a) and root aluminum versus root potassium (b) concentrations in sugar maple seedlings grown in soil culture.

root. This binding reduces the bioavailability of both Al and P (Foy et al. 1978).

The question arises "Do we have an excess of Al or of PO_4 inside the plant". If we convert the values in Fig. 2-7a to equivalents and assume that binding is 1:1 based on equivalents (PO_4^{3-} and Al^{3+}) we discover that there is a 10 fold excess of Al for binding. If we assume that Al is in a univalent form (Al^{+}) and thus the binding is 3:1 (Al:PO_4) we still have an excess of Al associated with the roots.

The next question that arises is "Is all of the Al inside the root and is all of the Al bound to PO_4". Histochemical stains revealed that a considerable amount of the Al was bound externally to the root surface (Plate 2-4) possibly to organic ligands. Therefore, we do not know how much of the total Al associated with the root was bound to PO_4 within the root. Nor do we know how much free PO_4 is present in the root.

The ratio of $AlPO_4$ to that of free PO_4 is important in terms of P nutrition and P deficiency. Kinch and Hutchinson (pers. comm.) found that sugar maple seedlings grown in the laboratory on soils collected from declining sites grew poorly. Addition of P greatly improved their growth which suggested a P-deficient soil as one of the reasons for the poor growth of sugar maple. The degree to which the P deficiency was induced by acid rain and $AlPO_4$ binding is not known.

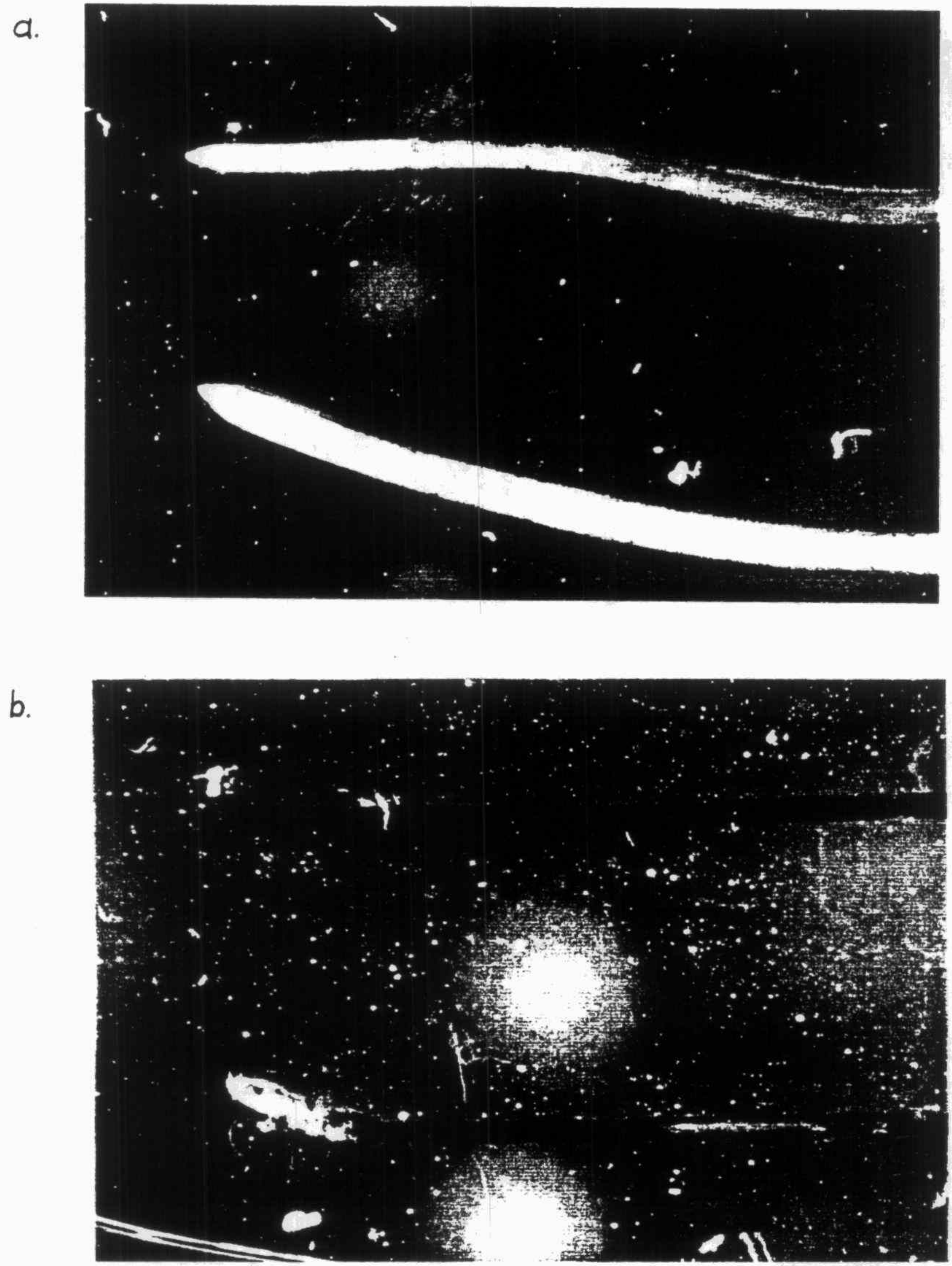


Plate 2-4. Roots of sugar maple seedlings (a) exposed to Al, and (b) exposed to Al and stained with hematoxylin. Purple areas are locations of Al.

Root Al was also negatively correlated with root K (Fig. 2-7 b, not significant at P=0.05). Potassium leakage is known to be a reliable indicator of stress. However, in this experiment, stress in the form of severe drought was associated with higher not lower root K concentrations. This suggests that K leakage, to be used reliably, would need to be standardized for the amount of rainfall. Potassium leakage, or rather lower root K concentrations is among the more sensitive parameters of stress in this experiment.

Calcium and Mg were positively correlated in the shoots as were Mg and Mn (Table 2-4). One interesting result is that Mn was negatively correlated with total N in the shoots. Manganese is another trace metal that is mobilized at low pH and can be toxic if present in sufficiently high concentrations (Foy and Fleming 1978). So far most of the attention has been focused on Al-P and Al-Ca interactions and not on Mn-N interactions which may be important, especially since N is frequently the limiting nutrient in forest ecosystems. In the present experiment, tissue concentrations of N were high and do not indicate N-deficiency (Tables 1-2, 1-3).

The results from this experiment are inconclusive since the soil was not inherently sensitive to acidification and thus the pH did not decrease sufficiently during this 4 week experiment to release large stores of bound Al into solution. However, this experiment does shed some light on nutrient deficiency and metal bioaccumulation. It suggests that chemical composition of sugar maple may be a very sensitive indicator of decline if decline is due to edaphic factors.

Table 2-4. The coorelation matrix for element concentrations in shoots of sugar maple seedlings grown in soil culture.

	Al	**Cl**	**Ca**	**K**	**Mg**	**Mn**	**N**	**P**
Al	1							
Cl	.056	1						
Ca	-.064	-.043	1					
K	-.092	.287	.168	1				
Mg	-.068	.283	.407	.094	1			
Mn	-.132	.156	.18	.033	.318	1		
N	.192	.247	.053	.117	.118	-.314	1	
P	.023	.034	.007	.097	.151	-.04	.108	1

N=43
FOR SIGNIFICANCE=0.05, R>= 0.288
FOR SIGNIFICANCE=0.01, R>= 0.372

PART 3: SPONGE/SAND EXPERIMENT

INTRODUCTION

The purpose of this experiment was to separate the effects of low pH from those of elevated Al. This is not possible if soil (as in the previous experiment) is used as the rooting medium since low pH and elevated Al concentrations are linked. Instead an inert rooting medium consisting of sponge and silica sand was used after we tested several "inert" media including rock wool and perlite, both of which had trace contaminants of Al, Mn, Ca, Mg, and P (Appendix 2). The sponge was added to the sand to increase its water-holding capacity since we needed to control the water regime to induce drought.

METHOD

Sugar maple seedlings were exposed to various pH (5.5, 4.5, 3.5), drought (control, intermediate, severe as in the soil experiment), and elevated Al concentrations (0, 20, 100, and 250 ppm). Plants were watered with Ingestad Solution (Appendix 2). Replicates consisted of 4 pots with 3 plants per pot. All three plants were combined to provide sufficient biomass for chemical analysis. Plants were grown in the greenhouse for 4 weeks. They were then harvested as in the soil experiment and analyzed for root and shoot biomass, root and shoot area, as well as tissue concentrations of Al, Mn, Ca, Mg, Na, Cl, K, P, and N (Appendix 2 for methods and Appendix 5 for raw data).

RESULTS AND DISCUSSION

Plant Biomass

In this experiment the inert medium did not buffer the pH thus the initial pHs were probably similar to those to which the roots were exposed. Also there was little organic matter to bind with Al. Although no significant effect on root and shoot biomass or area was observed, roots appeared more stunted in the high aluminum treatments (plate 3-1).

Plant Chemistry

One of the most consistent results was an increase in root and shoot Al concentrations with increasing levels of treatment Al and with decreasing pH (Figs. 3-1 and 3-2). This increased uptake of Al confirms our hypothesis that Al becomes more bioavailable at low pH. Similar results have been shown for a variety of crop species (Foy 1974). Aluminum concentrations in the shoots reflected concentrations in the roots (significantly correlated $P \leq 0.01$) but were approximately 15 times lower (Table 3-1, Fig. 3-8). Since only the soil was watered with the acidic Al-contaminated "rain" elevated concentrations in the shoots indicates that Al was translocated during the experiment.

Another consistent result, which was an experimental artifact, was an increase in both root and shoot Na with increasing treatment-Al at pH 5.5 and 4.5 (Fig. 3-3). After Al was added to the nutrient

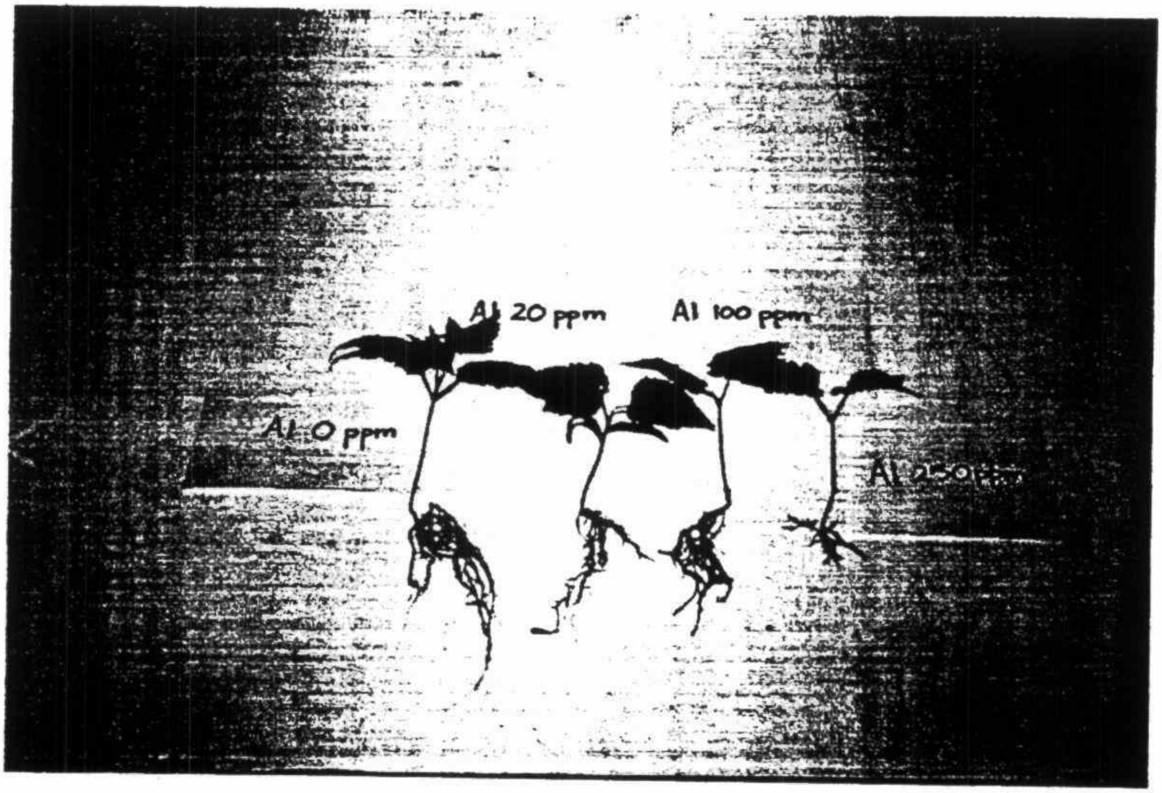


Plate 3-1. Typical growth of the roots of sugar maple seedlings grown in sponge/sand culture after one month exposure to different Al concentrations.

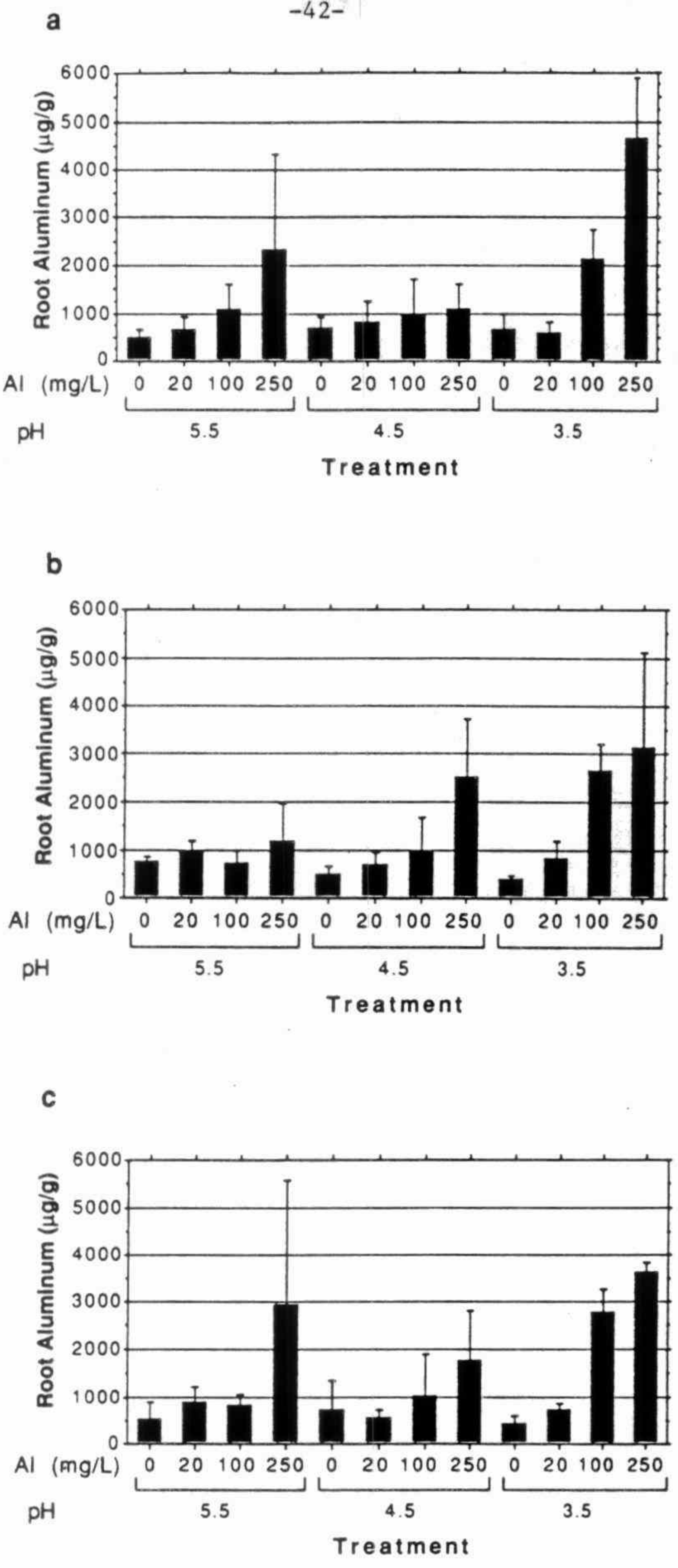


Figure 3-1. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on root aluminum concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture.

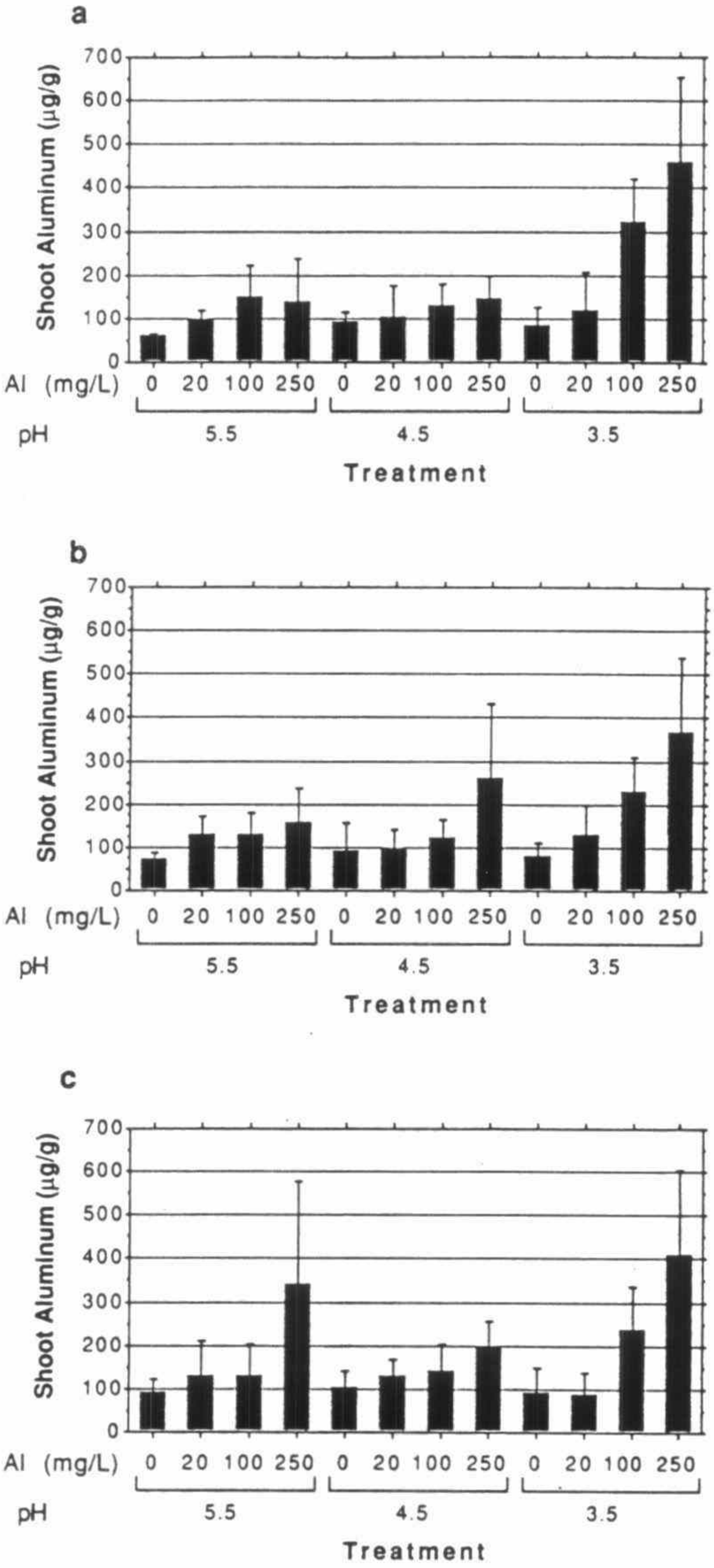


Figure 3-2. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on shoot aluminum concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture.

Table 3-1. The coorelation matrix for element concentrations in roots versus shoots of sugar maple seedlings grown in sponge/sand culture.

ELEMENT	COUNT	CORRELATION	R-SQUARED	SIGNIFICANCE
Al	144	0.689	0.475	0.001
Ca	144	0.334	0.111	NS
Cl	144	0.124	0.015	NS
K	144	-0.045	0.002	NS
Mg	144	0.385	0.148	NS
Mn	135	0.377	0.142	NS
N	144	0.550	0.302	0.001
Na	141	0.638	0.407	0.001
P	144	0.440	0.194	0.01

(NS=not significant)

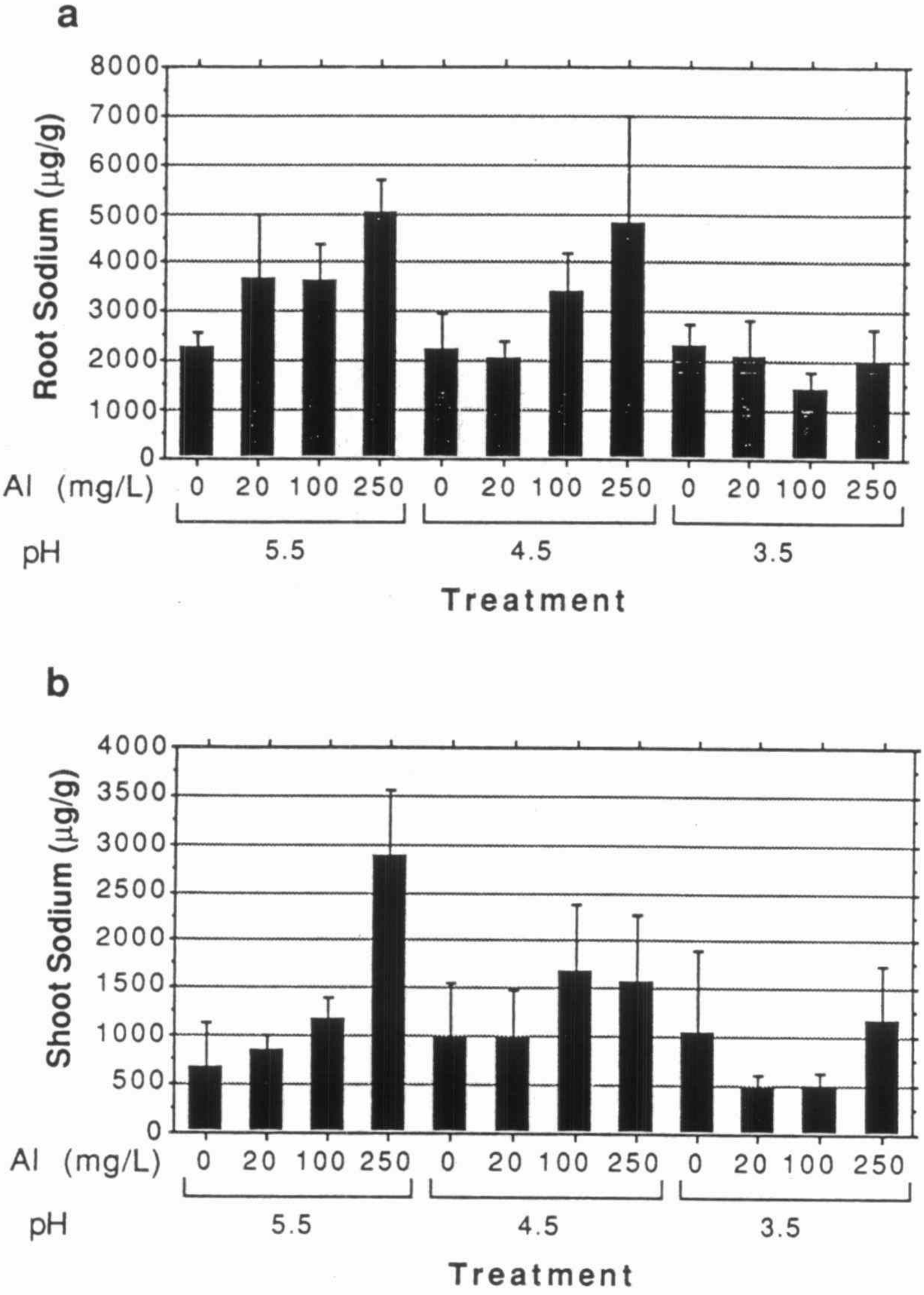


Figure 3-3. The effect of varying pH and aluminum treatments on root sodium (a) and shoot sodium (b) concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture.

solution to give the desired concentration, NaOH was added to adjust the pH. Since Al is an acid buffer, more NaOH had to be added to overcome the acidifying effect of Al. Hence at the higher pHs in the presence of elevated Al, more Na was present in the "rain". Sugar maple readily accumulated this Na and translocated it to the shoot (Fig. 3-8 b). Although this has little bearing on the effects of acid rain, it does provide some insight into the potential effects of road salt. Sodium is known to produce an osmotic stress similar to drought and may be harmful if present in sufficiently high concentrations in tissue (Bowen 1979).

Aluminum and Ca are known to compete for exchange sites (Foy et al. 1978, Foy and Fleming 1978). Studies have shown that Al toxicity is very much a function of the amount of Ca available for uptake (Foy 1974). If ratios of Ca to Al drop below 1, the toxicity of Al increases significantly. In the present study concentrations of Ca in the nutrient solution were 3.5 mg/L or 0.18 meq/L. Concentrations of Al were 0, 20, 100, and 250 mg/L which gives meq/L of 0.74 for the monovalent form to 2.2 for the trivalent form at 20 mg/L. Therefore all of the treatments except for the control had Ca:Al ratios less than 1. Despite this, Ca concentrations in the roots were so variable that no significant trend was obvious. Calcium concentrations in the shoots were lowest at pH 3.5 and 250 mg Al/L in the control drought, were variable in the intermediate drought, and decreased with increasing Al in the severe drought treatment (Fig. 3-4) which does support the displacement hypothesis.

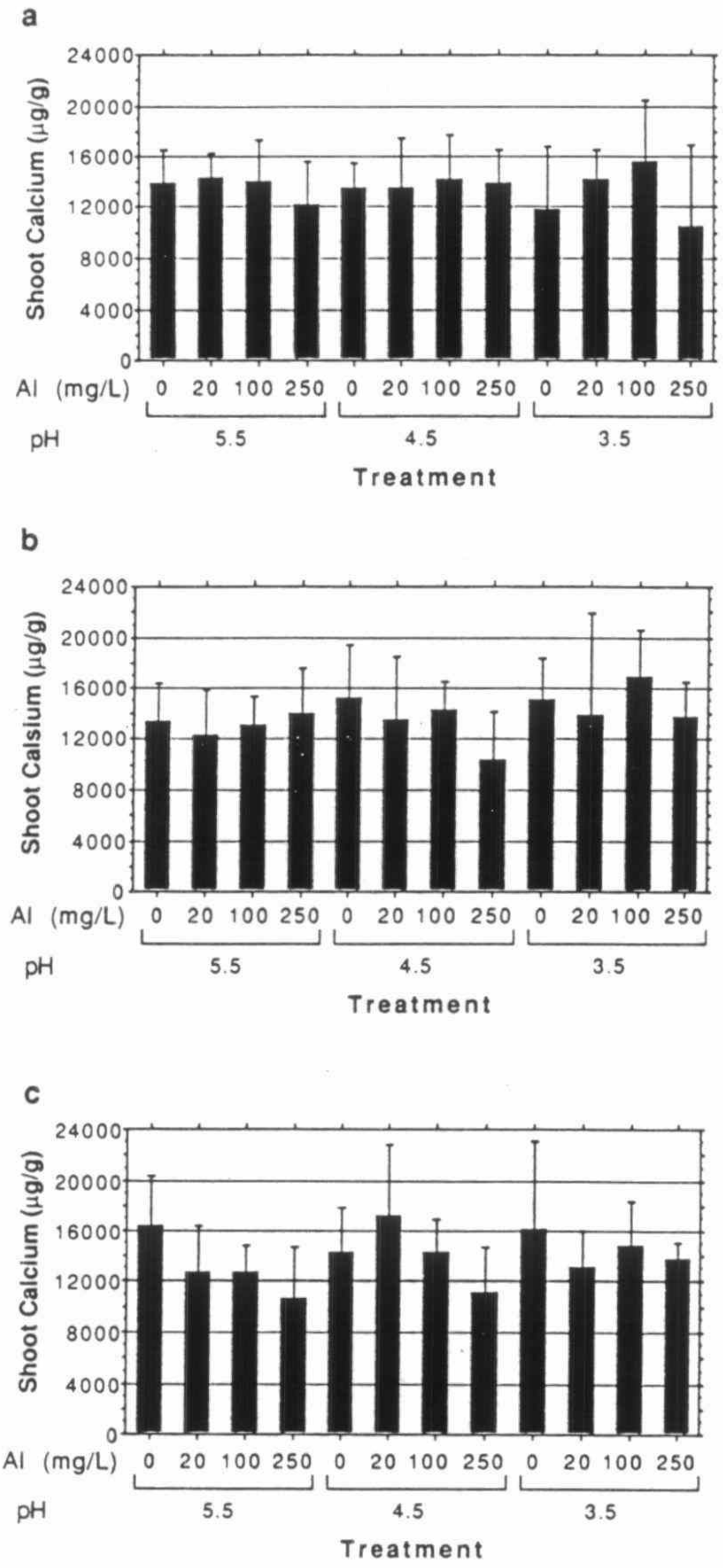


Figure 3-4. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on shoot calcium concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture.

Magnesium, which is also a divalent cation like Ca, more clearly supported the displacement hypothesis. Root Mg concentrations decreased with increasing Al at pH 3.5 in all of the drought treatments (Fig. 3-5).

Phosphorus, a nutrient known to bind with Al, was also highly variable in the roots and showed no consistent trends. In the shoots, concentrations decreased with increasing Al at pH 3.5 in the control drought, were highly variable in the intermediate drought, and increased with increasing Al in the severe drought and thus no conclusion can be drawn from these results (Fig. 3-6).

Potassium concentrations in the roots decreased with increasing concentrations of treatment Al in all of the three droughts (Fig. 3-7). In this experiment it was one of the most sensitive parameters and may be useful as an early warning indicator of Al stress. Potassium leakage was less pronounced in the severe drought treatment, which once again suggests that in order for K-leakage to be a reliable indicator of stress, water availability would have to be standardized or at least known not to be an additional stress.

Of all the elements only root vs shoot Al (r^2=0.475, $P<0.01$), Na (r^2=0.407, $P<0.01$), and N (r^2=0.302, $P<0.05$) were significantly correlated (Figs. 3-8) with higher concentrations in the roots reflected in the shoots.

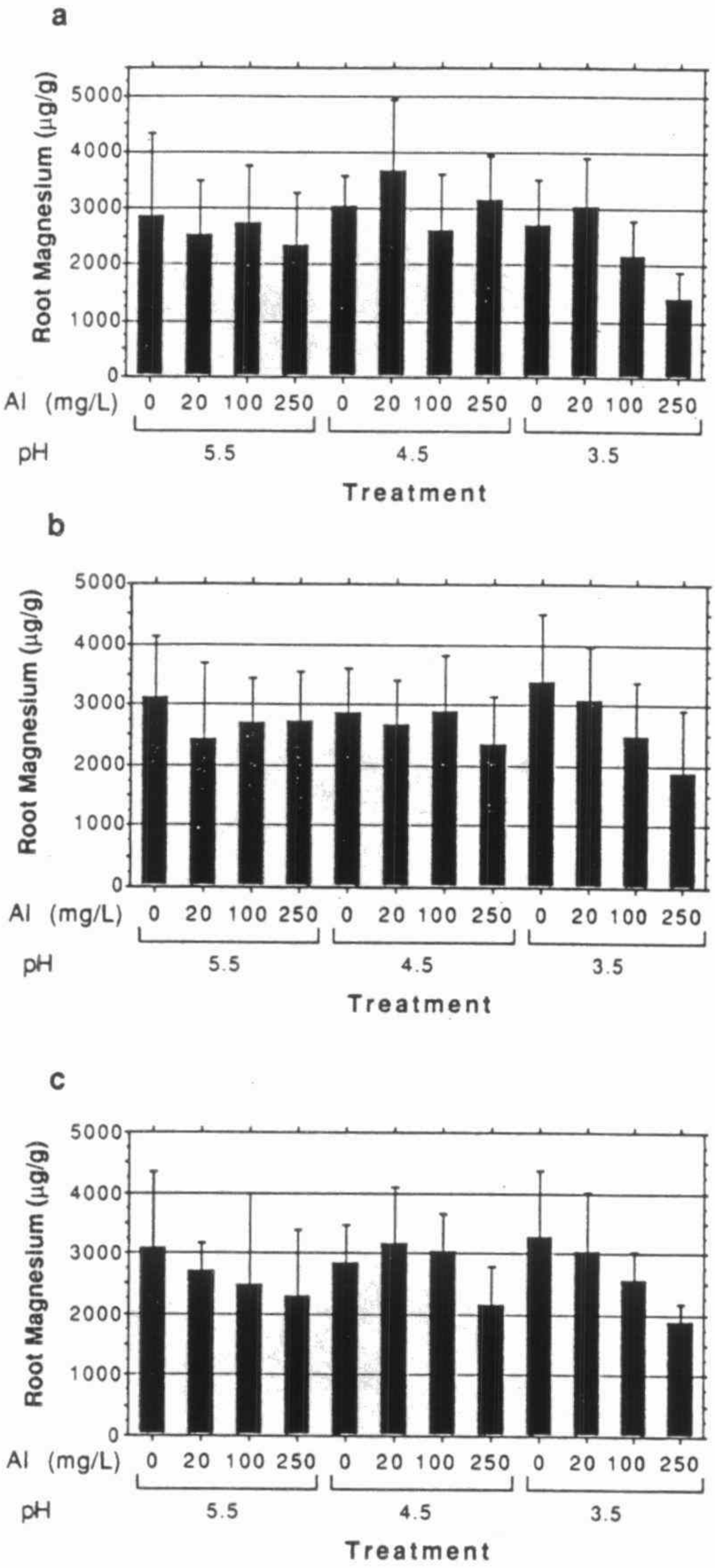


Figure 3-5. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on root magnesium concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture.

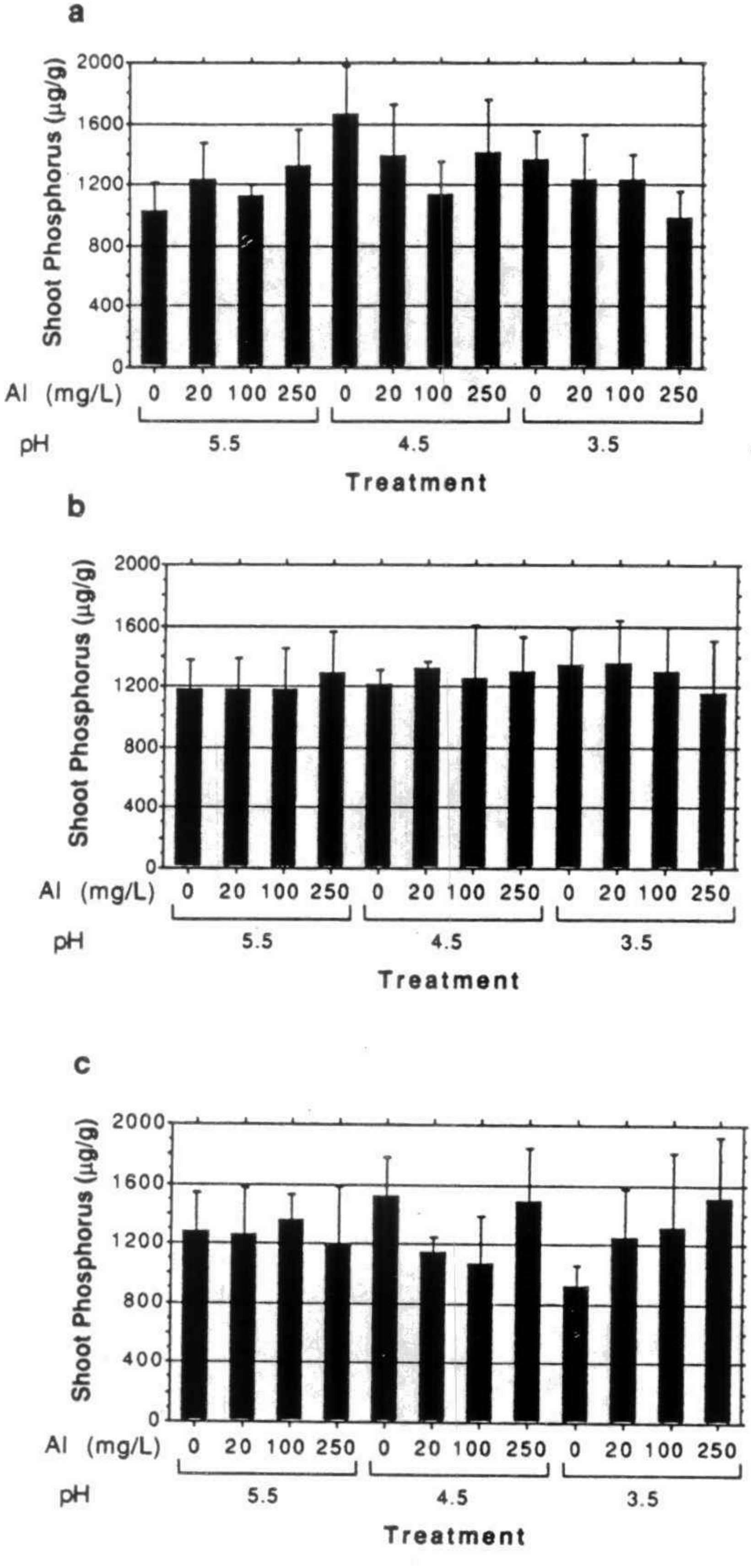


Figure 3-6. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on shoot phosphorous concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture.

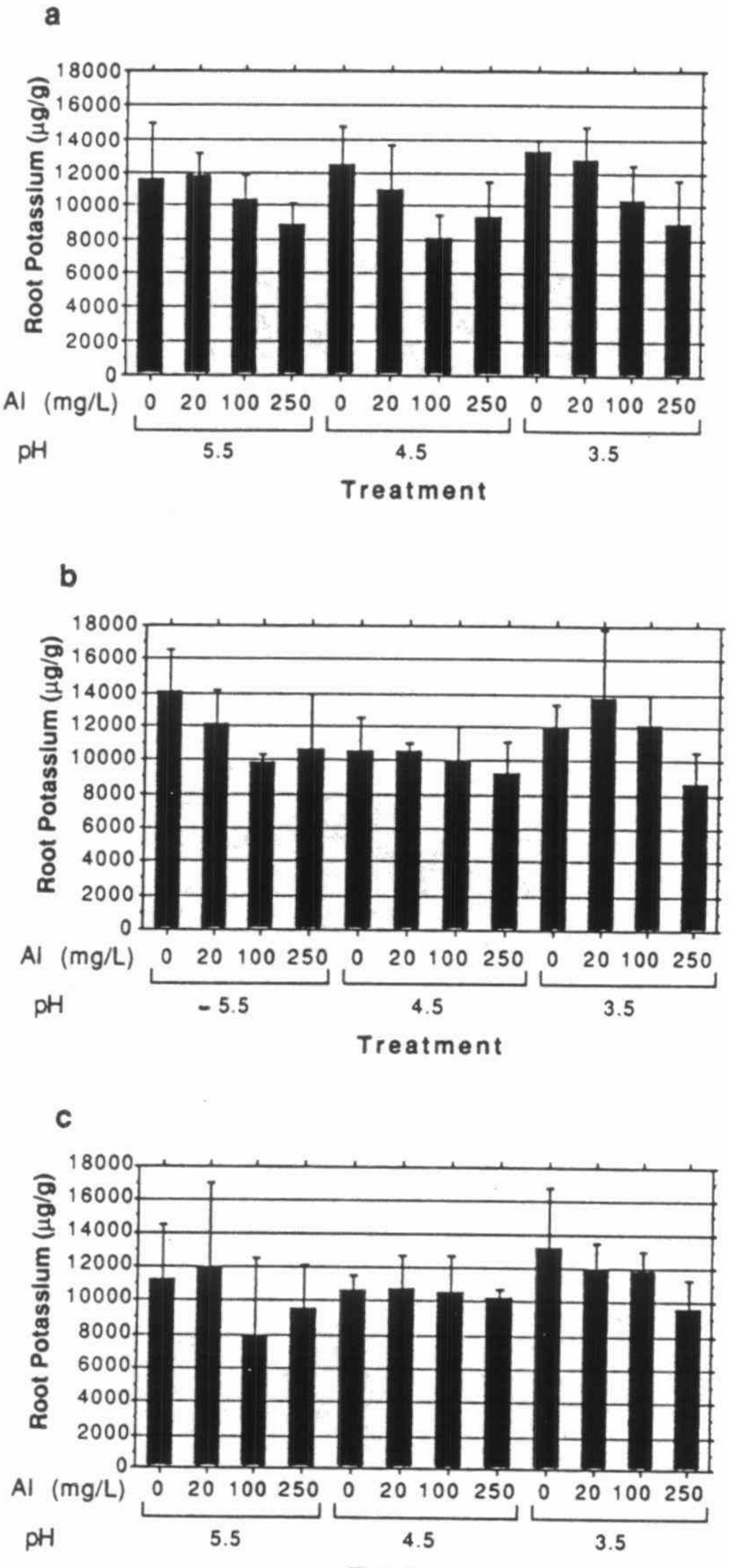


Figure 3-7. The effect of varying pH, aluminum and drought treatments (a=control, b=intermediate, c=severe) on root potassium concentrations (+/- one standard deviation) in sugar maple seedlings grown in sponge/sand culture.

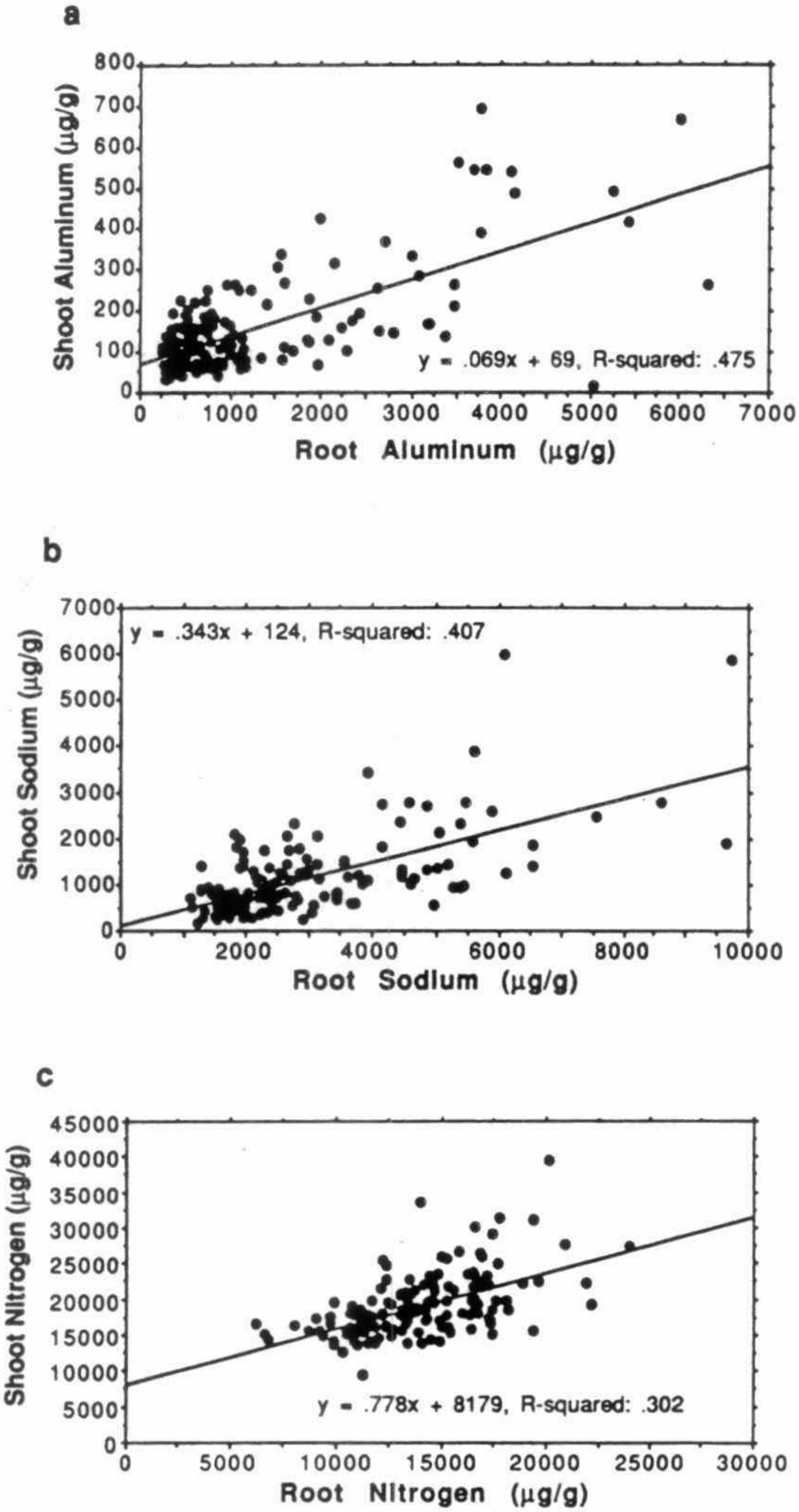


Figure 3-8. Root concentrations versus shoot concentrations of aluminum (a), sodium (b), and nitrogen(c) in sugar maple seedlings grown in sponge/sand culture.

Within the roots (Table 3-2) some elements were positively correlated (N/P, Ca/Mg, and Al/Mn) while others were negatively correlated (Mg/Al) (Fig. 3-9). The negative correlation between Al and Mg supports the displacement hypothesis shown in the soil experiment. Interestingly the relationship between Al and Ca was once again not significant.

One result that seems to re-occur is the positive correlation between root Al and root Mn (Fig. 3-9). Both of these metals are mobilized at low pH and perhaps it is not surprising that they correlate. However, in the inert medium the most likely source of Mn is the nutrient solution. The mostly likely source of Mn in this experiment is the nutrient solution (Appendix 2).

The positive correlation between N and P and between Ca and Mg was also noted in the soil experiment and is not a function of the acid, aluminum or drought treatments.

The correlation matrix for shoots (Table 3-3) shows that some of the elements are positively correlated (N/P and Ca/Mg at $P<0.01$, Fig. 3-10) and that none are negatively correlated. The negative correlation between Al and Mg observed in the roots was not observed in the shoots which suggests that translocation of these two elements may differ.

Table 3-2. The coorelation matrix for element concentrations in roots of sugar maple seedlings grown in sponge/sand culture.

	Al	Ca	Cl	K	Mg	Mn	N	Na	P
Al	1								
Ca	-.384	1							
Cl	-.235	-.055	1						
K	-.166	-.128	.343	1					
Mg	-.582	.669	.173	.129	1				
Mn	.463	-.223	-.049	.129	-.226	1			
N	.274	-.352	-.01	.146	-.411	.194	1		
Na	.136	-.117	.248	-.129	-.228	.053	.316	1	
P	.337	-.245	-.027	.212	-.211	.269	.575	.23	1

N=134
FOR SIGNIFICANCE=0.05, R>= 0.169
FOR SIGNIFICANCE=0.01, R>= 0.221

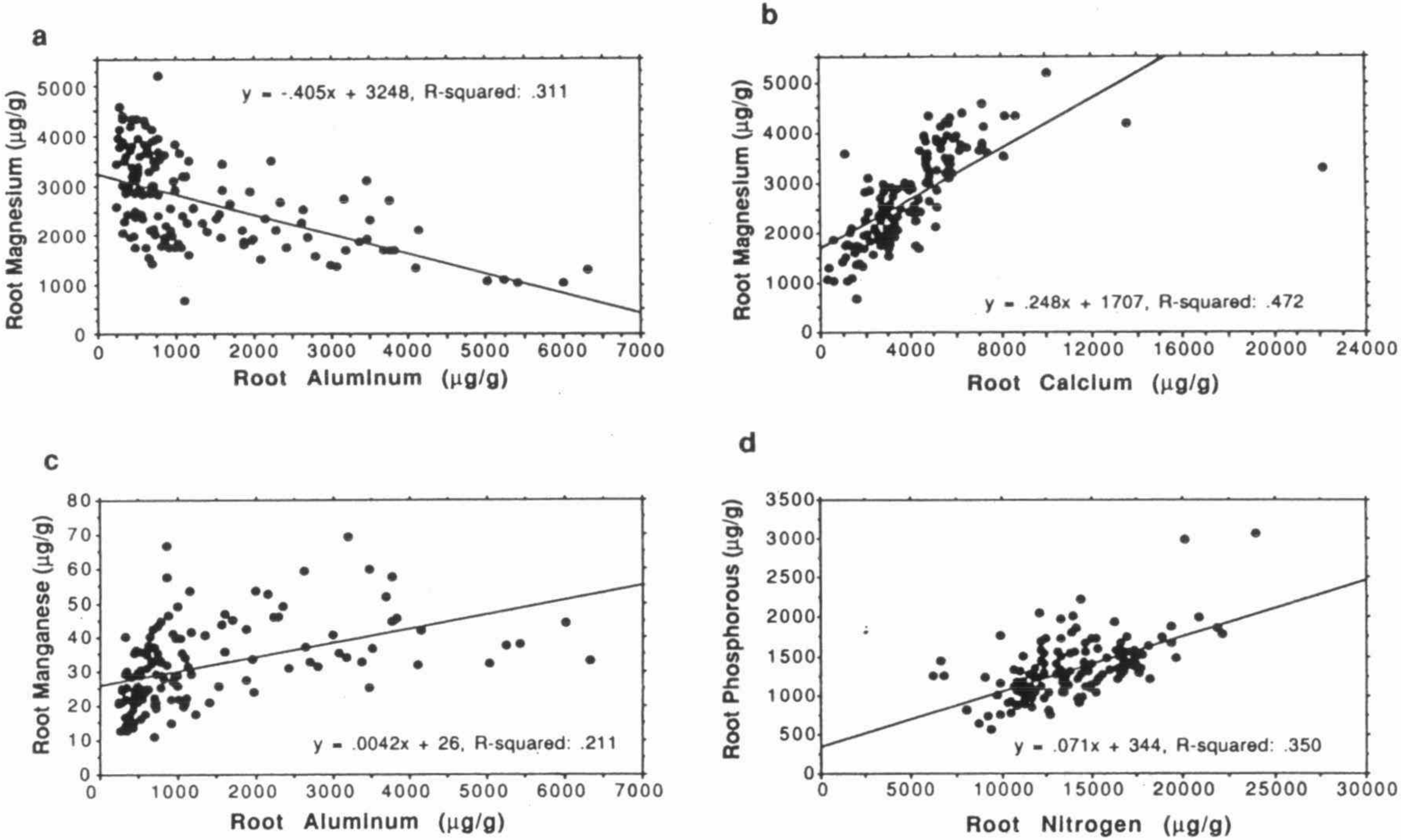


Figure 3-9. Root concentrations of aluminum versus magnesium (a), calcium versus magnesium (b), aluminum versus manganese (c), and phosphorous versus nitorgen (d) in sugar maple seedlings grown in sponge/sand culture.

Table 3-3. The coorelation matrix for element concentrations in shoots of sugar maple seedlings grown in sponge/sand culture.

	Al	Ca	Cl	K	Mg	Mn	N	Na	P
Al	1								
Ca	-.102	1							
Cl	.219	.253	1						
K	-.038	-.149	.04	1					
Mg	.02	.696	.36	-.17	1				
Mn	.372	.015	.366	.016	.064	1			
N	.348	-.402	.346	.108	-.288	.218	1		
Na	.181	-.401	.156	.16	-.337	-.031	.428	1	
P	.05	-.175	.354	.055	-.09	.247	.587	.239	1

N=142

FOR SIGNIFICANCE=0.05, R>= 0.168

FOR SIGNIFICANCE=0.01, R>= 0.220

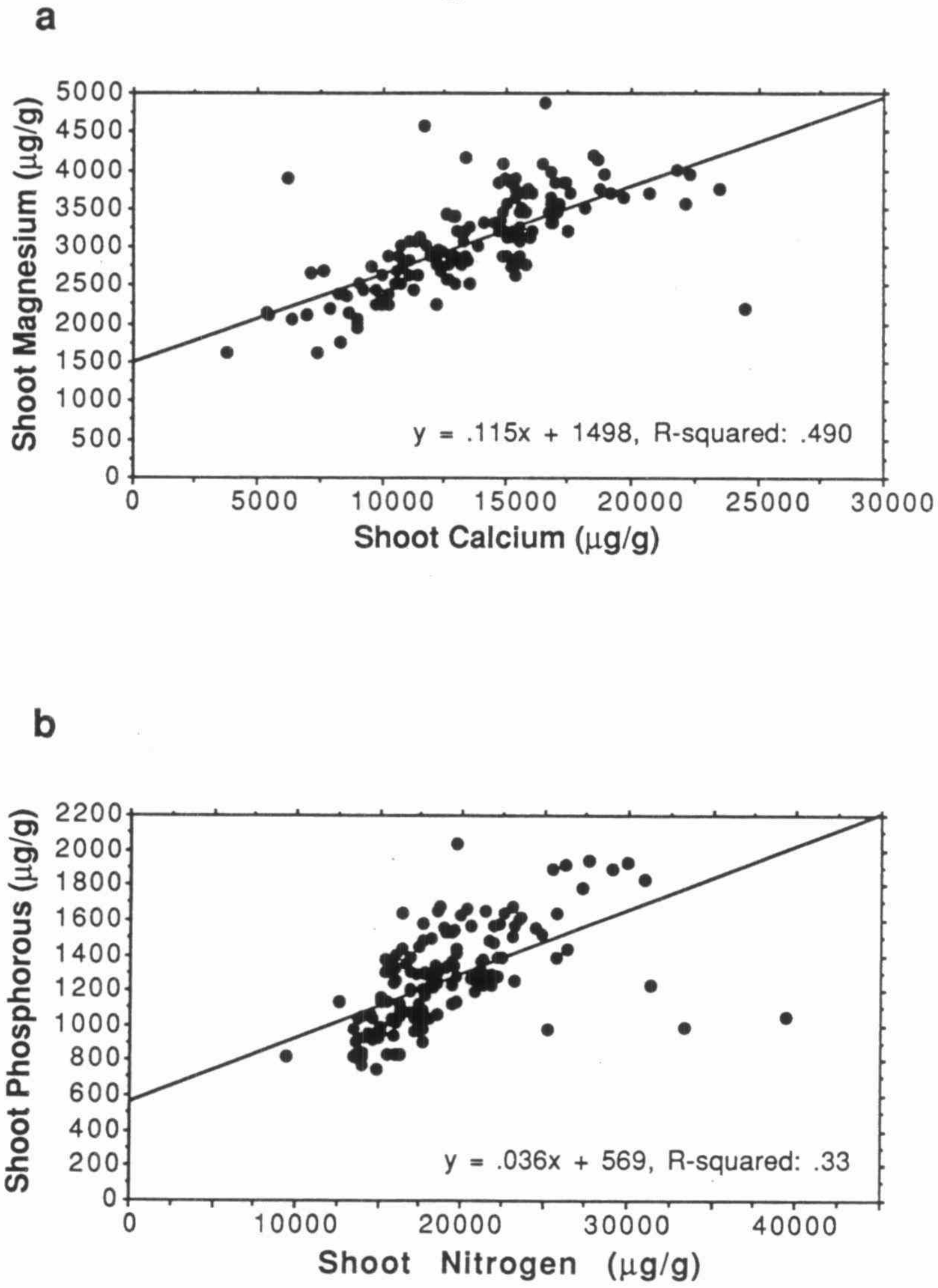


Figure 3-10. Shoot concentrations of calcium versus magnesium (a) and phosphorous versus nitrogen (b) in sugar maple seedlings grown in sponge/sand culture.

PART 4: WATER CULTURE EXPERIMENT

INTRODUCTION

We had inherent difficulties controlling drought in both the soil and the sponge/sand experiments and decided to try a water culture with polyethylene glycol (PEG) as the drought initiator. PEG produces an osmotic stress but can also be toxic to plants. For this reason plants were placed into semi permeable membrane bags which kept the PEG on the outside but allowed water and nutrients to enter inside the bag and to come in contact with the roots. This technique enabled us to maintain a constant drought and also to test simultaneously the effects of low pH and elevated Al concentrations.

METHOD

Several tests were run to determine the right concentrations of PEG. At one point we tested this procedure with one year old white spruce (*Picea glauca*) as well. White spruce and sugar maple differed in their response to the treatments and both are included in the discussion.

To impose drought, polyethylene glycol (PEG, Carbowax; molecular weight 15,000-20,000; obtained from Fisher and Union Carbide) was added to the water culture. This substance attracts and binds water molecules, thus reduces the amount of water available for plant uptake. Plant roots were enclosed in a semi-permeable dialysis membrane (Spectra/Por 1) to prevent direct contact between the roots and the potentially toxic PEG. This membrane allows roots and the potentially toxic PEG. This membrane allows penetration of molecular weights smaller than 8,000 but inhibits passage of the larger molecular weight PEG.

We tested (1) the permeability of the dialysis membrane to Al, macronutrients, PEG, and dissolved oxygen; (2) the concentration of PEG that would induce a moderate drought stress in sugar maple; and (3) the effects of transplant shock (see Appendix 3 for methods and Appendix 6 for raw data; see also Plates 4-1 to 4-4).

To develop and refine these procedures we ran 4 sets of experiments, 3 with sugar maple and 1 with white spruce. The first experiment was run for 12 days (June 25, 1987 to July 7 1987) and consisted of the following 8 treatments: Al--0 and 50 mg/L, PEG--0 and 100 g/L, pH 5.5 and 4.0 (Appendix 3). Results of seedling growth are based on 6 replicate plants per treatment. These are pseudo replicates since all the "replicate" plants were within the same chamber. The high cost of each chamber and the difficulty of managing 48 pumps precluded true replicates.

The second experiment was conducted for 14 days (August 12 to 26, 1987) and was similar to the first experiment except for the following differences: we used (1) older seedlings (3 months vs 1 month), (2) lower concentrations of PEG (25 g/L), and (3) the Ingestadt (1962) nutrient solution which had relatively higher concentrations of P, Ca, K compared with those of N (Appendix 3).

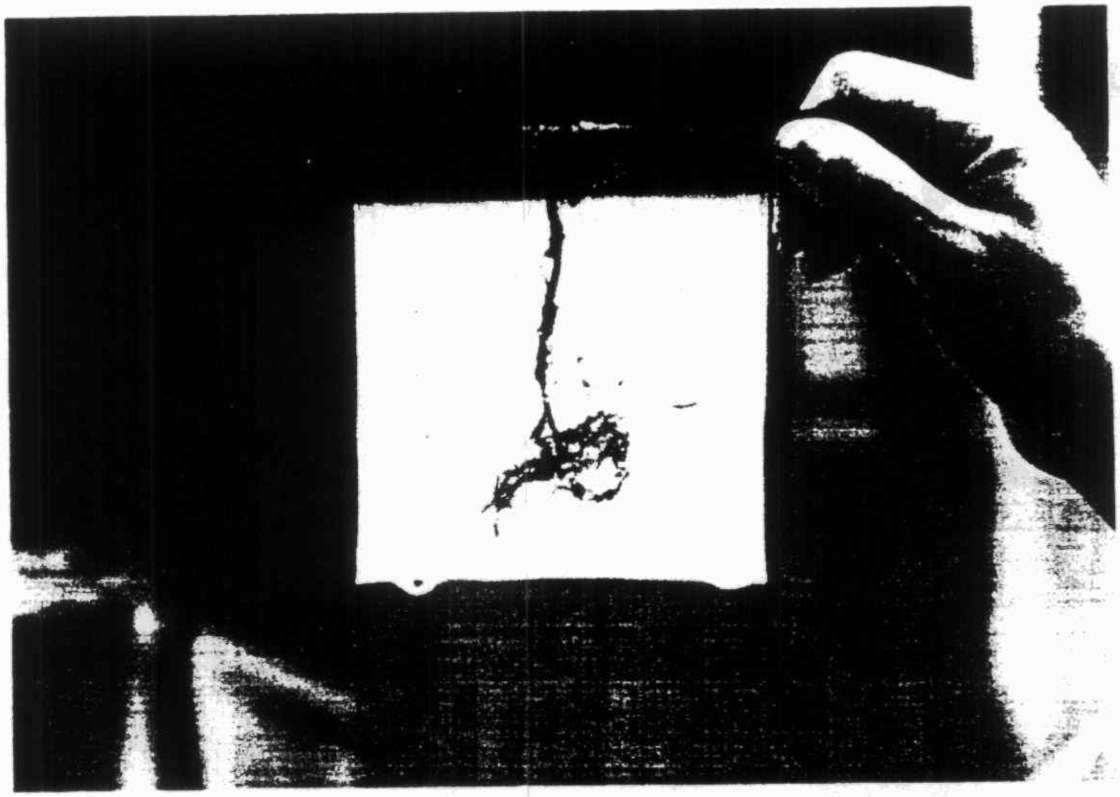


Plate 4-1. A sugar maple seedling with its root enclosed in a dialysis membrane.

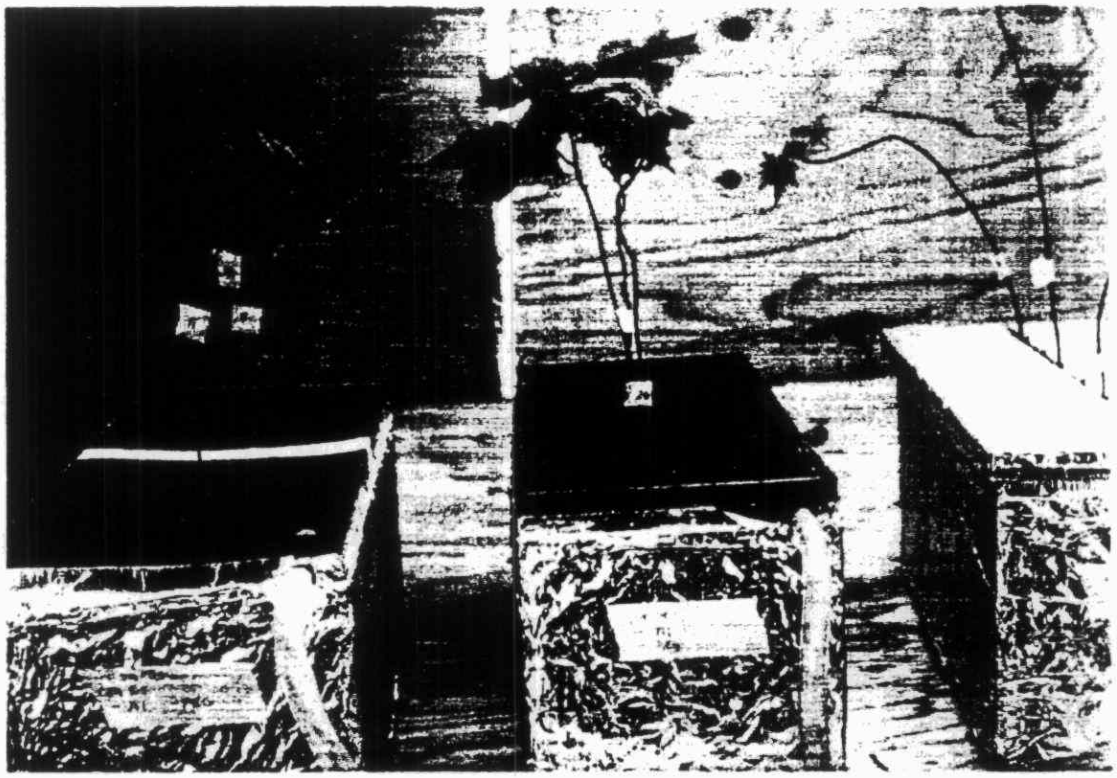


Plate 4-2. Sugar maple seedlings growing in a growth chamber.

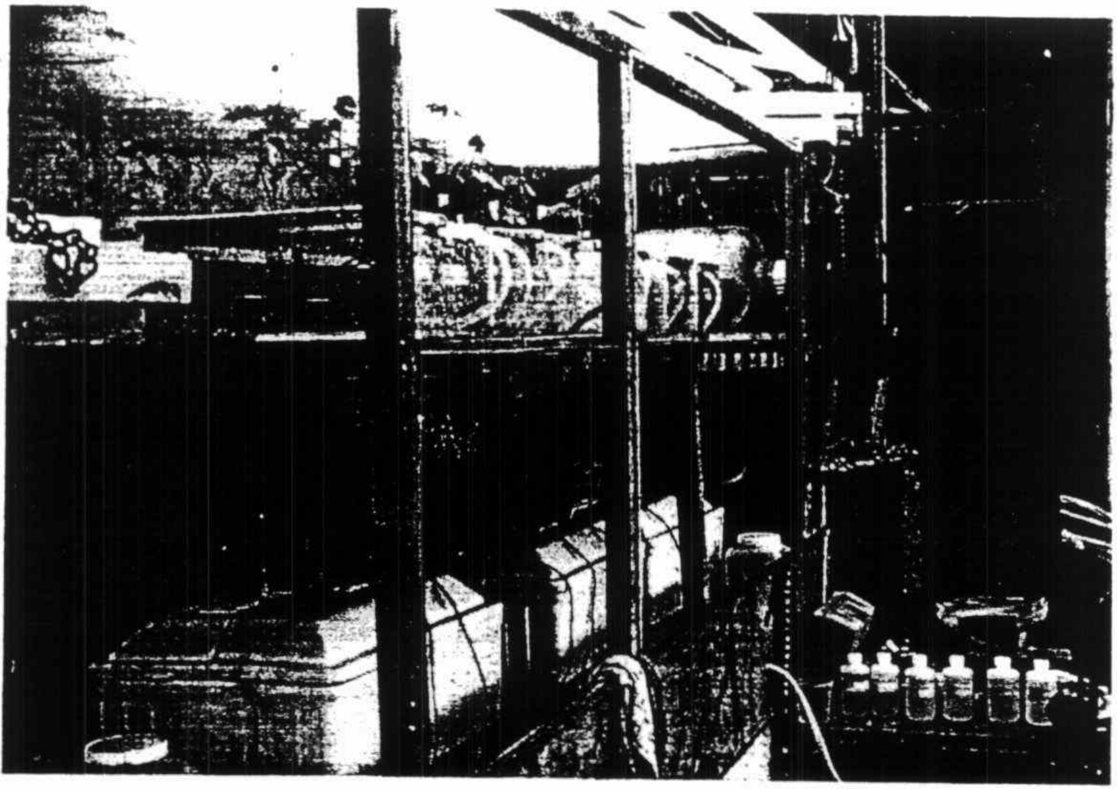


Plate 4-3. Experimental setup of the nutrient solution experiment in the Mining Building greenhouse.

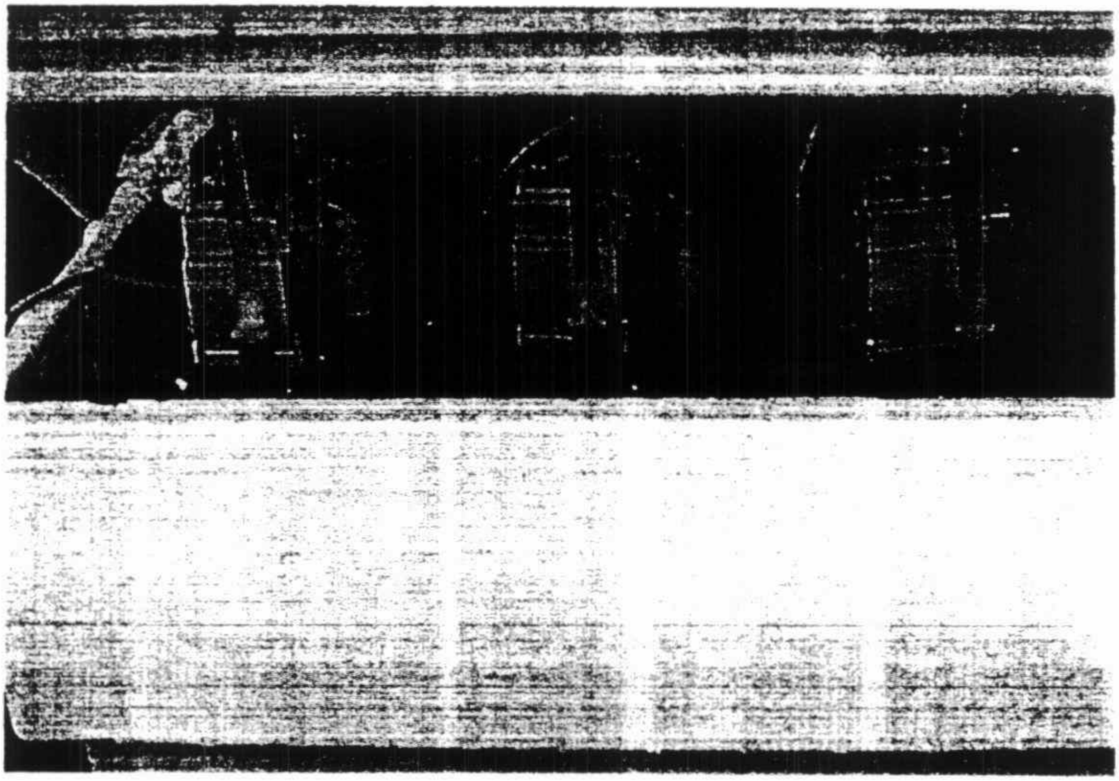


Plate 4-4. Pumps circulate the nutrient solution through growth chambers. Styrofoam containers filled with ice packs keep the solution cool.

The third sugar maple experiment ran for 14 days (March 2 to 16, 1988) and was similar to the previous experiment except that 2 year old sugar maples were used. Since these plants were much larger than the seedlings we reduced the pseudo replicates from 6 to 3.

We also tested this method with one year old white spruce on October 5-29, 1987 (21 days). In this experiment we used the Ingestadt (1971) nutrient solution, 120 g/L of PEG, and 3 plants per treatment. The pH and Al were identical to those in the first experiment (i.e. pH 5.5 and 4.0, Al 0 and 50 mg/L).

RESULTS AND DISCUSSION

Permeability of Dialysis Membrane

The dialysis membrane was permeable to Al, Ca, Cl, K, Mg, Mn, Na, and dissolved oxygen but was impermeable to PEG as shown in Table 4-1. Sodium is present as a contaminant in PEG and was found both inside and outside the membrane in the PEG treatment.

Sugar Maple: Plant Biomass

In the first experiment the PEG concentration of 100 g/L (equivalent to -2.2 bar osmotic potential) was excessively high and the plants lost a considerable amount of wet weight within 5 days (Figure 4-1 a). In the second experiment the PEG concentration was designed to simulate field water potentials near Dorset, Ontario more closely (data provided by Bill Gizyn, Ontario Ministry of the Environment).

Table 4-1. Concentrations of elements and molecules inside and outside the dialysis membrane after 48 hours of submergence.

	SAMPLE	CONCENTRATION (mg/L)								
TREATMENT	LOCATION	Al	Ca	Cl	K	Mg	Mn	Na	O_2	PEG(g/L)
without PEG	outside	47	162	201	1120	179	8.4	<7	5.6	0
without PEG	inside	35	140	198	810	167	8.6	<8	6.0	0
with PEG	outside	48	156	187	1070	179	7.8	44	5.4	100
with PEG	inside	63	175	190	910	162	7.8	42	5.5	0

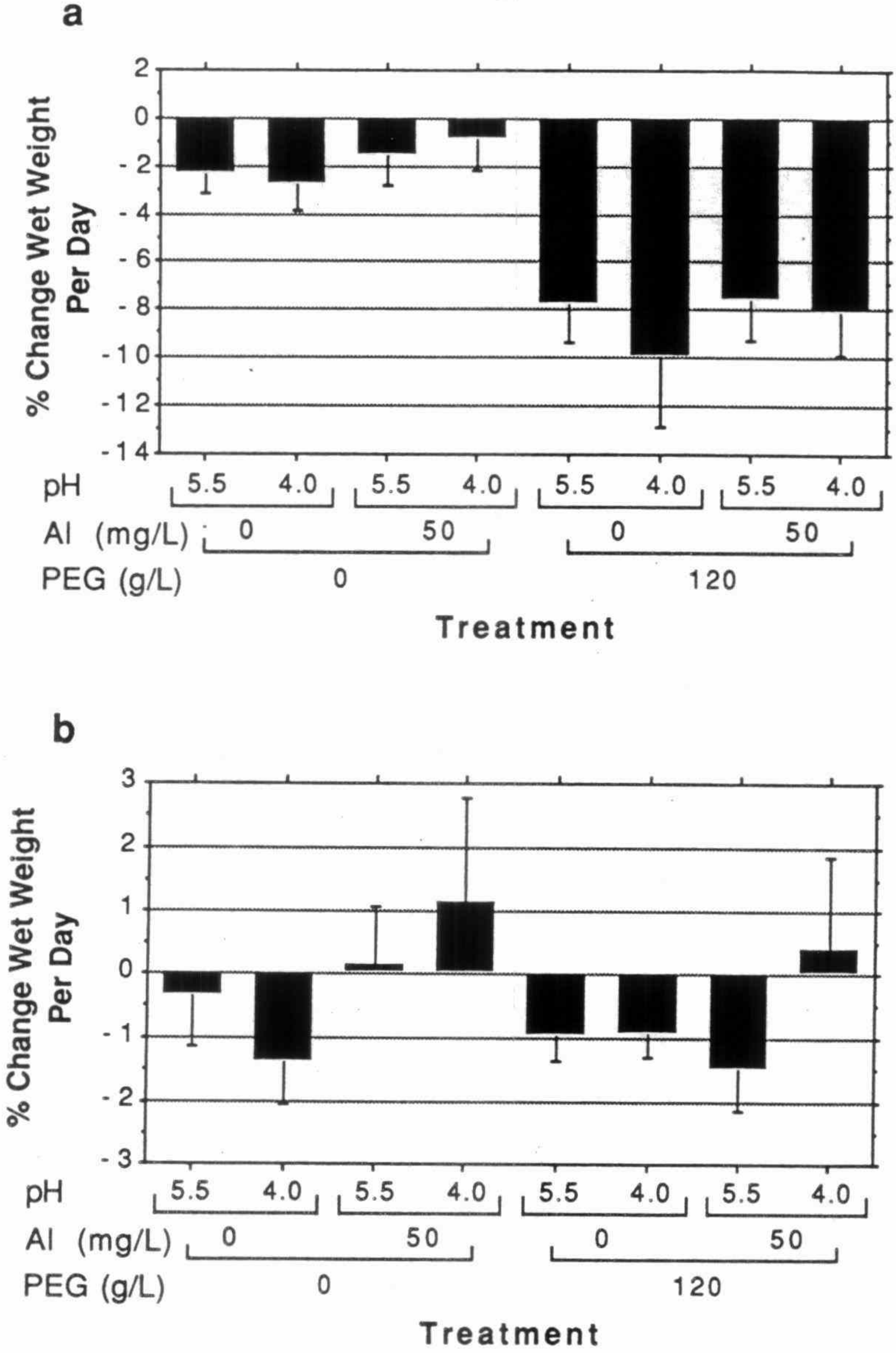


Figure 4-1. The effect of varying pH, aluminum and polyethylene glycol concentration on the percent change in wet weight per day (+/- one standard deviation) of sugar maple seedlings (a) and 2-year olds (b) grown in solution culture.

The PEG was reduced to 25 g/L and induced a mild drought stress (-0.5 bars) (Figure 4-1 b).

Once again there was little discernable effect of treatments on plant biomass. In the drought (+PEG) treatments wet weight was significantly lower but dry weight at harvest did not differ significantly (control vs treatments) (Fig. 4-2).

Sugar Maple: Plant Chemistry

The Al concentration in the sugar maple roots increased with lower pH, higher Al concentration, and lower PEG concentration (Fig. 4-3), while the opposite was true for Ca (Fig. 4-4, see also Tables 4-2 and 4-3). The shoot showed no differences for Al, and only a slight difference (in the same pattern as the roots) for Ca.

The Mg concentration in the roots decreased slightly in the presence of PEG but did not show the same trend as in the previous two experiments with soil and sand (Fig. 4-5).

The Cl concentration in the roots increased with lower pH, higher Al, and lower PEG (Fig. 4-6) probably because Al was added in the form of $AlCl_3$ and HCl was used to adjust the acidity of the nutrient solution.

Likewise the higher Na concentrations can be attributed to the use of NaOH to raise the pH and the presence of Na as an impurity in the PEG (Fig. 4-7, Table 4-2).

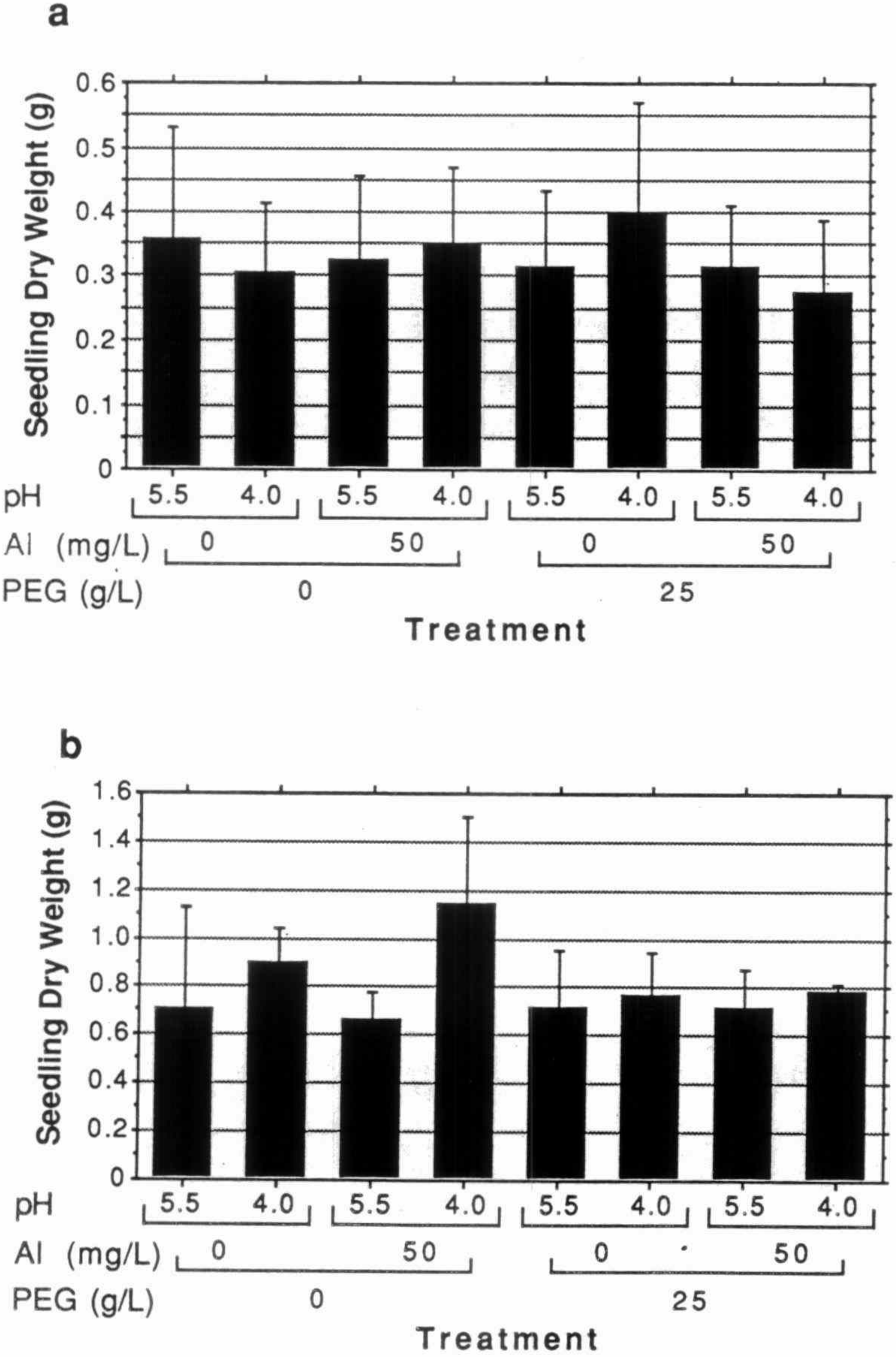


Figure 4-2. The effect of varying pH, aluminum and polyethylene glycol concentration on the total dry weight (+/- one standard deviation) in sugar maple seedlings (a) and 2-year olds (b) grown in solution culture.

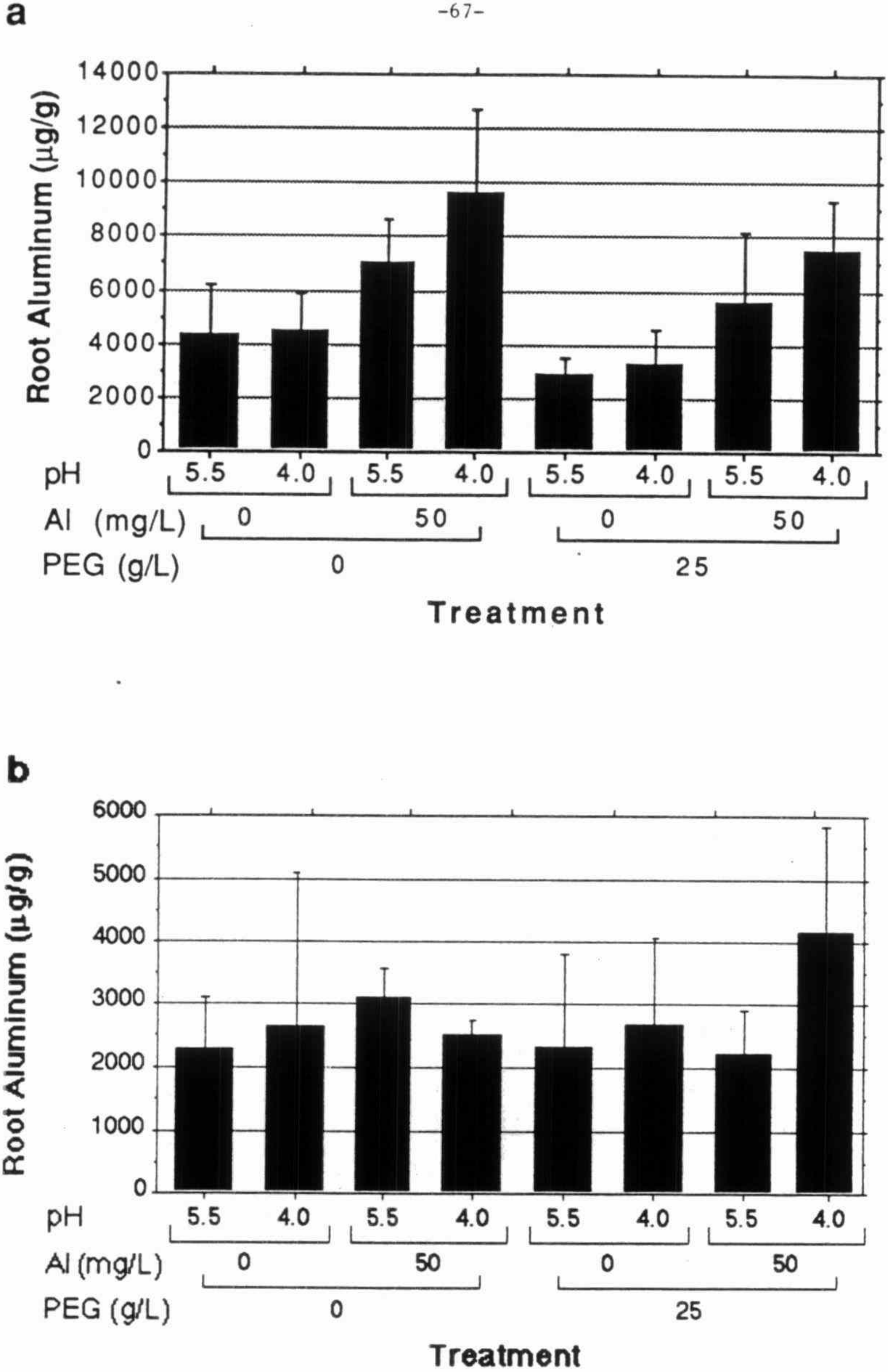


Figure 4-3. The effect of varying pH, aluminum and polyethylene glycol concentration on the root aluminum concentration (+/- one standard deviation) in sugar maple seedlings (a) and 2-year olds (b) grown in solution culture.

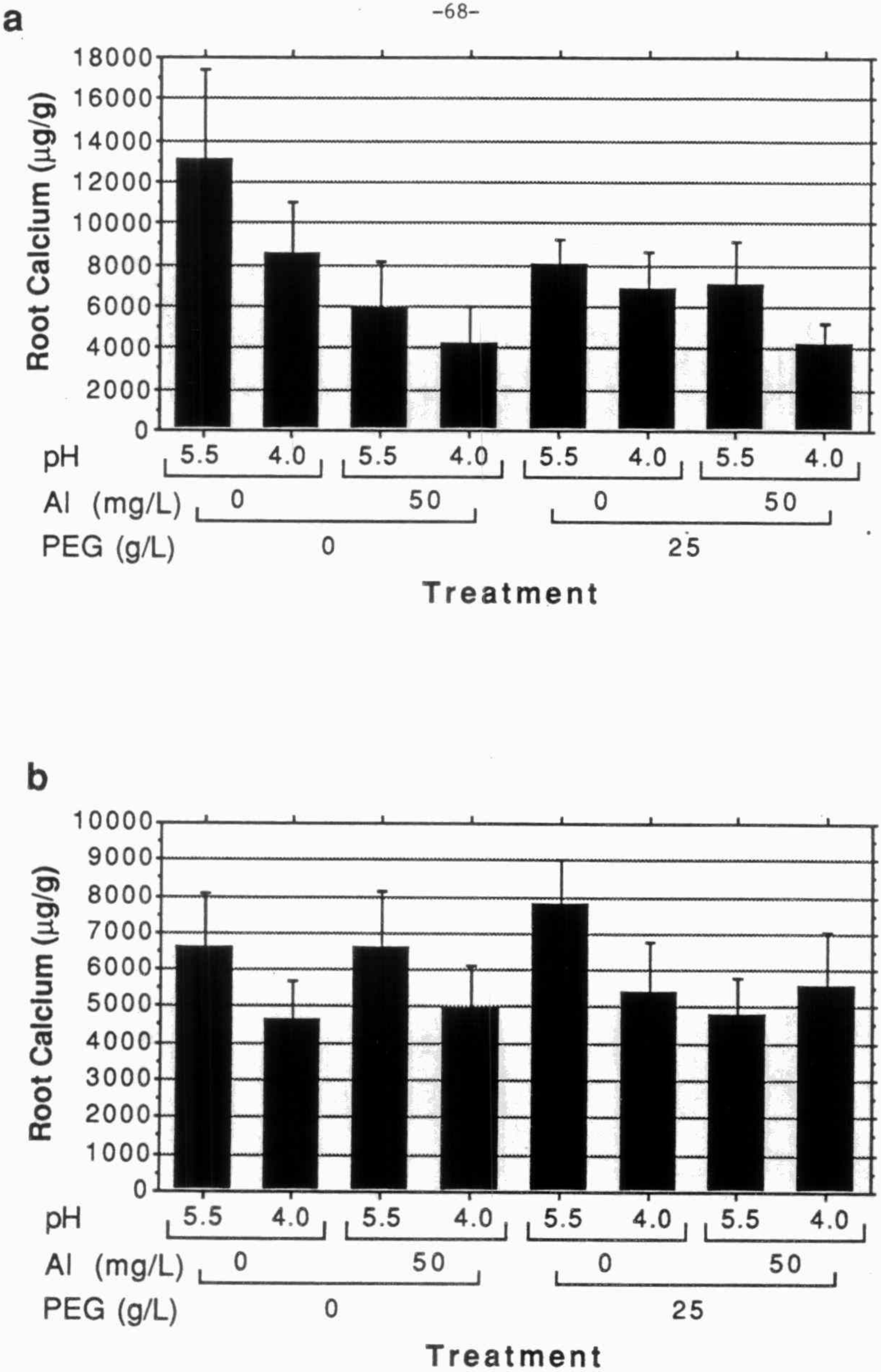


Figure 4-4. The effect of varying pH, aluminum and polyethylene glycol concentration on the root calcium concentration (+/- one standard deviation) in sugar maple seedlings (a) and 2-year olds (b) grown in solution culture.

Table 4-2. Treatment means of element concentrations with varying polyethyelene glycol concentration, aluminum concentration, and pH for sugar maple seedlings grown in water culture.

	PEG (g/L)	Al (mg/L)	pH	root Al	shoot Al	root Ca	shoot Ca	root Cl	shoot Cl	root K	shoot K	root Mg	shoot Mg
1	0	0	5.5	4365	2314	13050	26930	1670	3735	8940	9668	4353	3510
2	0	0	4.0	4518	1736	8547	22870	1680	2835	15200	12700	4005	2887
3	0	50	5.5	7008	2582	5920	23320	3798	5447	•	10240	4354	2987
4	0	50	4.0	9642	1858	4208	19950	4122	3885	13400	11550	4448	2820
5	25	0	5.5	2908	2577	8030	22420	1820	3495	10900	8990	2924	3078
6	25	0	4.0	3263	2557	6870	24120	1847	4667	22900	12275	2983	3633
7	25	50	5.5	5583	2080	7095	21500	2365	3530	•	10900	3725	3248
8	25	50	4.0	7473	2270	4188	19480	3715	4920	•	10455	3572	3430

	root Mn	shoot Mn	root Na	shoot Na	root Ti	shoot Ti	root U	shoot U	root V	shoot V
1	46.4	51.1	768	303	306	138	.70	.28	7.72	2.74
2	88.2	46.2	682	201	324	161	1.67	.83	6.45	2.61
3	89.6	61.6	1748	1815	348	185	1.95	1.14	5.77	3.21
4	61.8	43.1	916	374	493	183	2.51	1.27	5.64	2.31
5	95.3	55.7	752	367	262	171	3.02	1.38	5.38	3.14
6	46.3	49.1	784	548	261	190	1.20	1.31	4.52	3.65
7	68.0	46.8	2067	845	360	183	1.60	1.31	7.12	2.41
8	53.4	46.6	1130	578	349	186	2.26	2.15	4.97	3.03

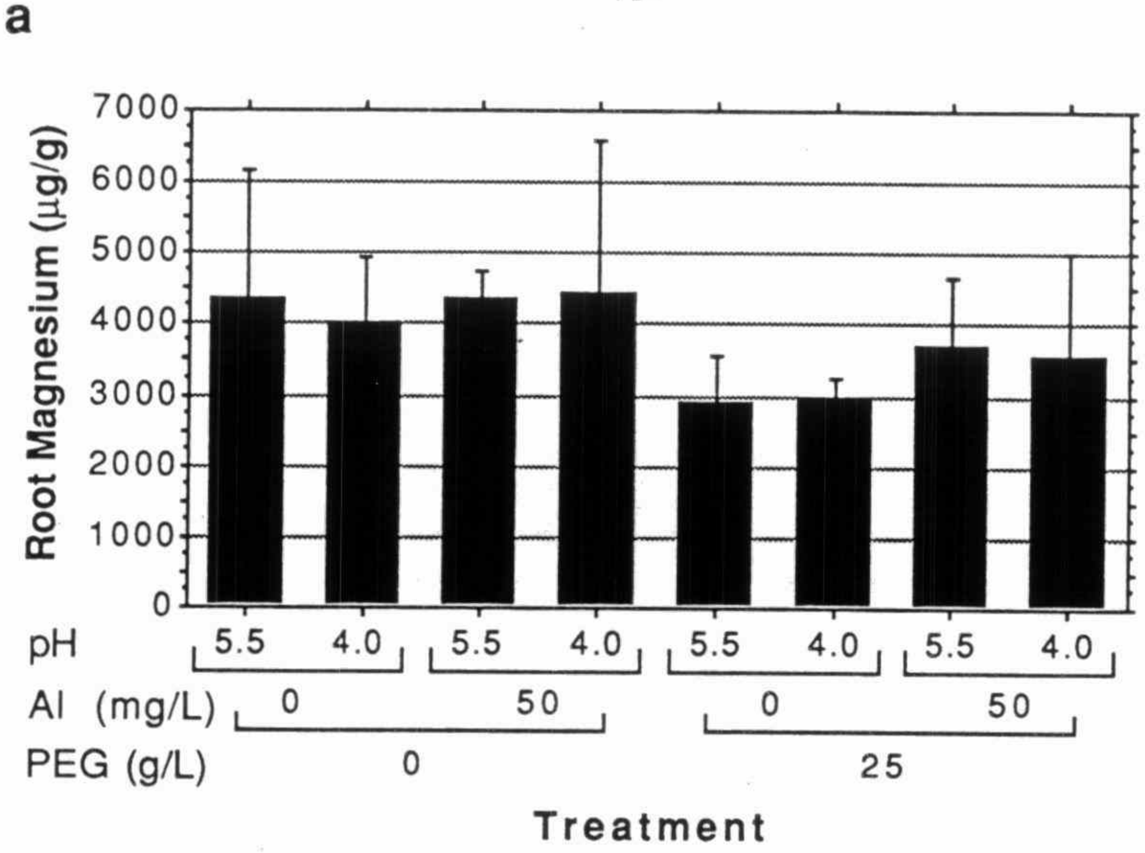
Table 4-3. Treatment means of element concentrations with varying polyethyelene glycol concentration, aluminum concentration, and pH for sugar maple 2-year olds grown in water culture.

	PEG (g/L)	Al (mg/L)	pH	root Al	stem Al	leaf Al	root B	stem B	leaf B	root Ba	stem Ba	leaf Ba	root Ca	stem Ca	leaf Ca	root Cr
1	0	0	5.5	2297	289	22.0	33.8	43.4	68.9	15.10	8.39	.987	6640	12600	4910	4.30
2	0	0	4.0	2660	201	10.5	45.2	25.3	59.8	11.00	5.94	1.330	4640	9430	4610	5.05
3	0	50	5.5	3130	384	22.7	41.1	49.8	82.2	12.30	7.54	1.080	6600	10900	5540	4.65
4	0	50	4.0	2510	264	52.2	39.7	29.3	38.9	3.86	6.50	1.360	4960	10300	4520	2.34
5	25	0	5.5	2315	302	36.0	38.2	48.4	67.2	39.20	7.17	1.970	7830	12000	4650	4.39
6	25	0	4.0	2673	510	20.4	36.4	51.3	68.9	12.30	8.86	1.510	5410	12200	4890	6.40
7	25	50	5.5	2243	174	15.0	37.3	46.4	91.9	8.95	6.44	1.490	4790	9400	5400	4.16
8	25	50	4.0	4173	287	31.9	39.2	32.8	87.5	6.23	7.12	1.230	5550	12000	5670	4.13

	stem Cr	leaf Cr	root Cu	stem Cu	leaf Cu	root Fe	stem Fe	leaf Fe	root Mg	stem Mg	leaf Mg	root Mn	stem Mn	leaf Mn	root Ni
1	.518	1.010	59.1	6.30	6.70	1660	116.0	•	1510	895	1424	230	93.7	43.6	5.32
2	.163	1.360	78.7	6.32	10.40	2100	46.0	14.8	1310	753	1720	152	56.3	97.2	36.80
3	.364	1.850	44.5	5.63	7.49	2040	164.0	21.7	1880	720	1440	342	93.7	130.0	6.36
4	.520	2.590	25.3	4.58	8.84	826	94.5	92.7	1006	652	1570	205	117.0	193.0	2.52
5	.795	2.210	49.7	4.87	10.70	1820	200.0	576.0	1580	941	1580	188	57.8	88.7	5.77
6	1.520	1.810	83.4	9.22	10.40	2330	258.0	198.0	1400	840	1450	186	91.8	110.0	5.87
7	.887	.988	83.5	6.61	7.54	1270	142.0	•	1470	898	1870	164	188.0	92.2	13.20
8	.755	2.710	37.3	4.87	10.20	1470	127.0	•	1240	739	1580	209	57.9	47.6	3.23

	stem Ni	leaf Ni	root P	stem P	leaf P	root Pb	stem Pb	root S	stem S	leaf S	root Si	stem Si	leaf Si	root V	stem V	root Zn
1	2.410	.884	1460	923	1690	15.0	4.20	1620	813	2060	118.0	11.7	17.10	4.73	.3160	77.9
2	.861	2.730	1880	1020	1700	23.6	12.80	1490	824	1990	149.0	13.8	5.37	5.39	.0530	36.2
3	1.430	1.600	1250	772	1970	64.5	6.04	1600	737	2230	36.7	30.4	13.70	5.49	.2400	74.8
4	1.400	3.000	1950	951	1680	14.2	4.25	1800	735	2190	62.2	28.7	10.40	2.37	.2760	25.4
5	1.160	.190	1280	866	2870	12.6	4.37	1420	767	2390	66.6	25.4	23.40	5.19	.4540	83.0
6	1.710	2.170	1570	939	2870	32.6	8.01	1410	802	2630	84.4	35.1	19.70	5.29	.7930	33.8
7	1.840	19.400	2170	1180	1100	16.3	3.51	2320	981	2160	49.5	14.9	10.10	3.62	.2440	49.5
8	2.290	2.460	2750	946	2590	13.9	4.38	1790	737	2210	56.3	17.8	6.39	4.05	.3460	26.1

	stem Zn	leaf Zn
1	15.4	14.5
2	11.9	17.3
3	16.9	18.4
4	11.6	14.1
5	15.3	25.2
6	17.1	21.3
7	15.0	23.7
8	15.2	20.8



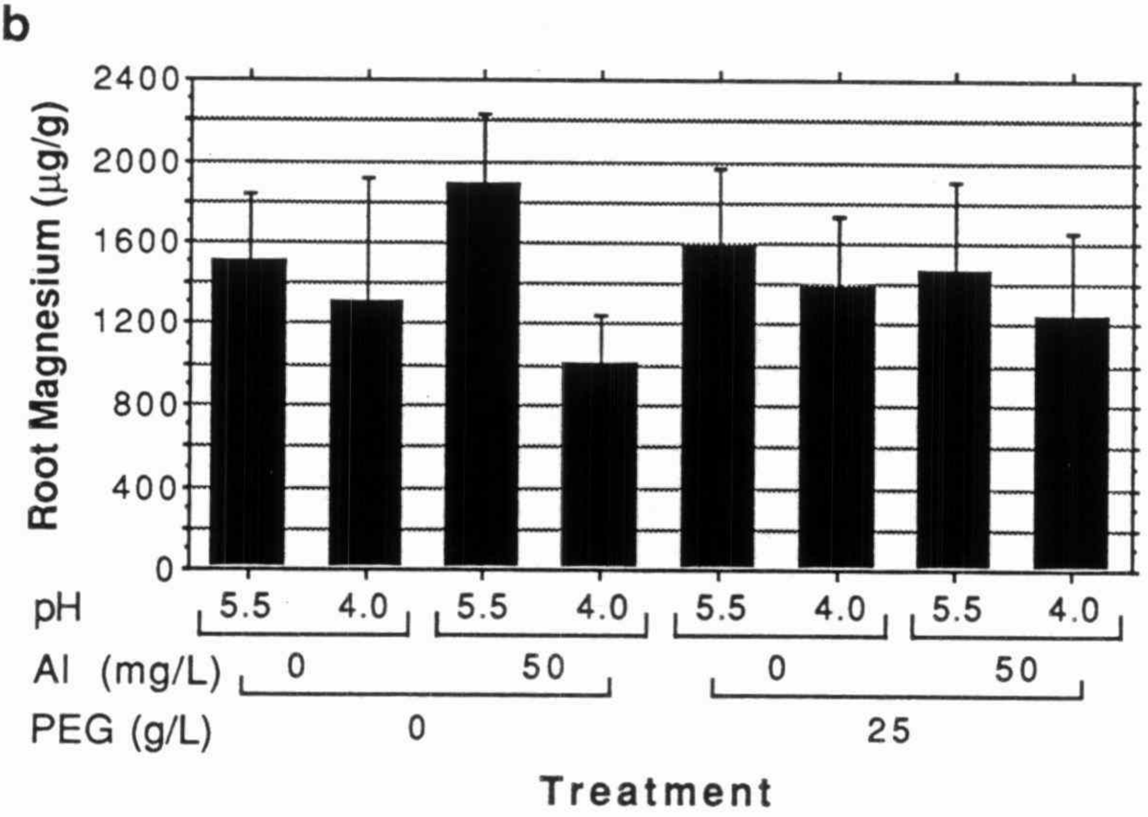


Figure 4-5. The effect of varying pH, aluminum and polyethylene glycol concentration on the root magnesium concentration (+/- one standard deviation) in sugar maple seedlings (a) and 2-year olds (b) grown in solution culture.

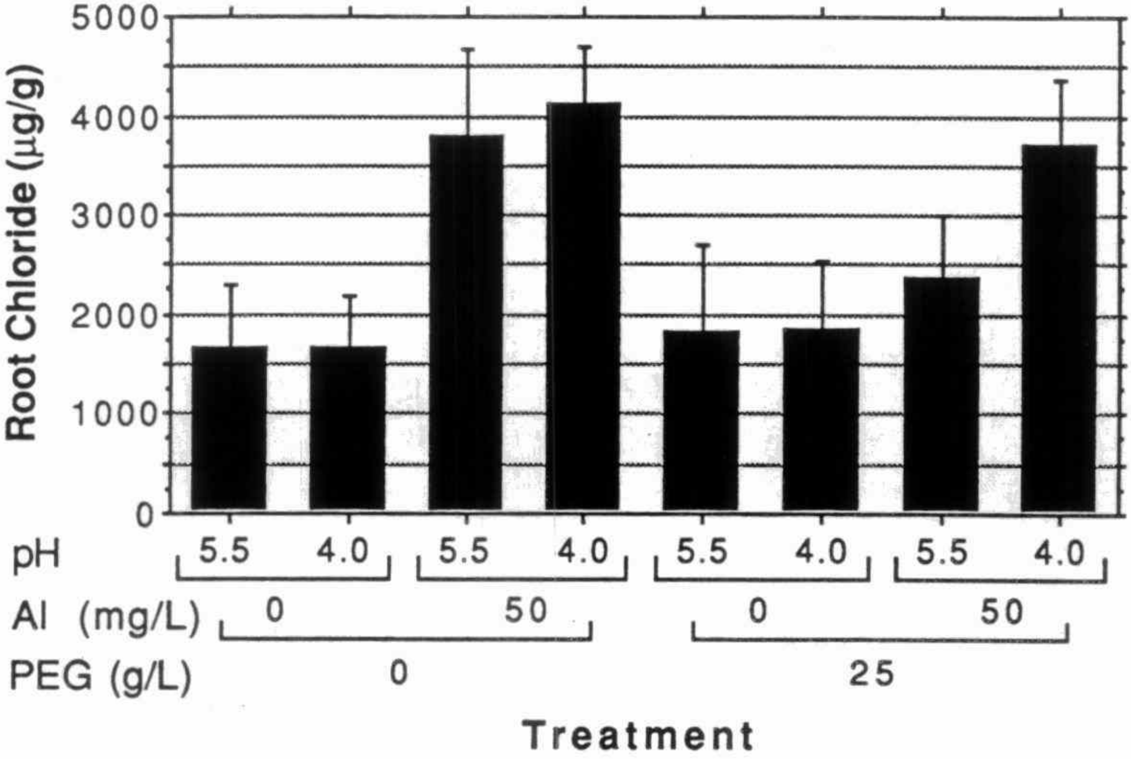


Figure 4-6. The effect of varying pH, aluminum and polyethylene glycol concentration on the root chloride concentration (+/- one standard deviation) in sugar maple seedlings grown in solution culture.

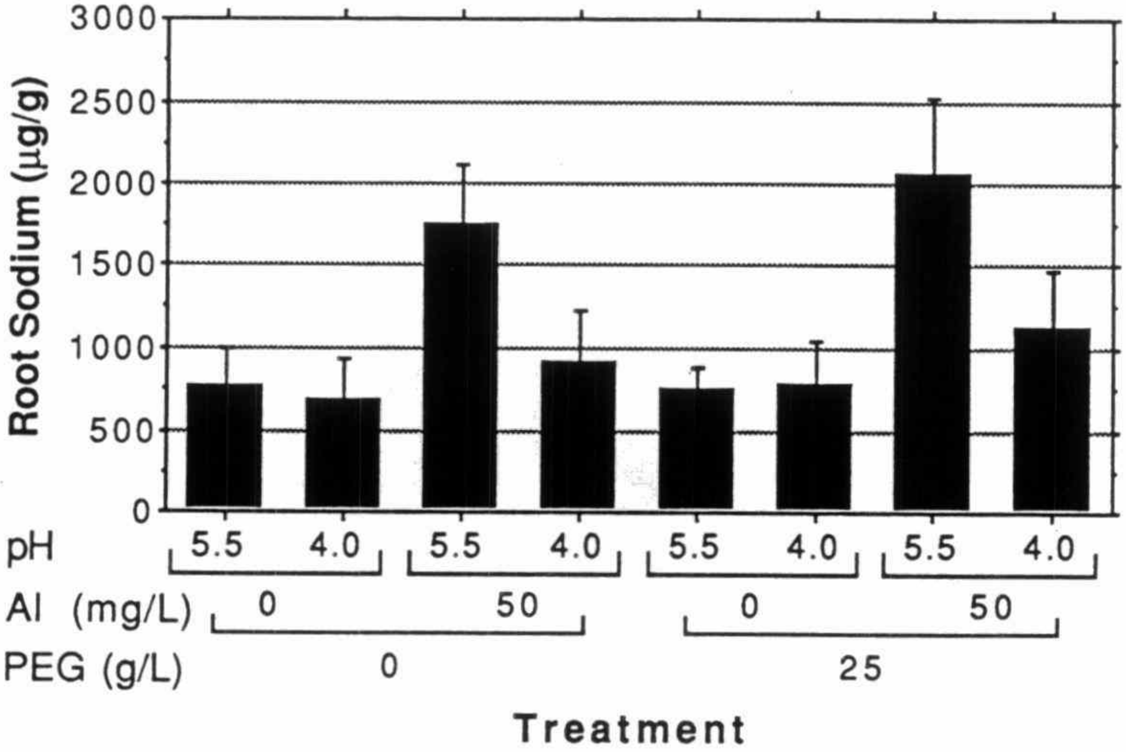


Figure 4-7. The effect of varying pH, aluminum and polyethylene glycol concentration on the root sodium concentration (+/- one standard deviation) in sugar maple seedlings grown in solution culture.

There was no significant correlation ($P \leq 0.05$) between the roots and the stems for Al, Ca, and Mg (Table 4-6). However, there were significant correlations within the roots for Al vs Mg, Fe, Cr, and V (Table 4-4, Fig. 4-8). Results for other elements not analyzed in the previous experiments can also be found in Table 4-4. Conditions which favour Al uptake may also favour uptake of the elements mentioned above. Positive correlations within the stem include Al vs Ca ($P<0.01$), which is contrary to the literature and contrary to what we found in the other experiments. Additional significant correlations can be found in Table 4-5. The only significant correlation in the leaves was between Ca and Ba both of which have similar chemical properties.

White Spruce: Plant Chemistry

The results for white spruce were similar to those of sugar maple for Ca, Na, and Cl but were different for Al (Fig. 4-9 and 4-10, Table 4-7). In white spruce Al concentrations in the roots remained low in all but one treatment, namely at pH 4.0, 50 ppm Al, and in the absence of PEG. Concentrations were 7 times higher than in any other treatment which suggests a threshold effect and not a step-wise effect as was evident in sugar maple (Fig. 4-3). High Al concentrations in the roots were reflected in both the stem and the needles of white spruce (Fig. 4-10, Table 4-7).

The drought treatment reduced the concentrations of Cl in the needles; Cl and K in the stem; and Cl, Mg, and Mn in the roots (Table

Table 4-4. The coorelation matrix for element concentrations in roots of sugar maple 2-year olds grown in water culture.

	Al	B	Ba	Ca	Cr	Cu	Fe	Mg	Mn	NI	P	Pb	S	SI	V	Zn
Al	1															
B	-.386	1														
Ba	.075	-.174	1													
Ca	.089	.118	.594	1												
Cr	.718	-.359	.347	.191	1											
Cu	-.033	-.136	.113	-.172	.449	1										
Fe	.751	-.394	.412	.162	.935	.375	1									
Mg	.537	-.396	.455	.395	.686	.278	.706	1								
Mn	.273	-.45	.138	.111	.168	-.107	.279	.506	1							
NI	.263	-.099	.037	-.165	.439	.526	.423	.224	-.13	1						
P	.112	-.015	-.474	-.526	-.317	.02	-.313	-.368	-.151	-.037	1					
Pb	-.009	.437	-.086	.241	.066	.007	.087	.016	-.235	.028	-.219	1				
S	-.118	.09	-.274	-.345	-.327	.165	-.275	-.003	.105	-.101	.566	-.168	1			
SI	.489	-.28	.15	.166	.591	.267	.591	.389	-.049	.5	-.204	-.113	-.23	1		
V	.778	-.423	.461	.247	.934	.291	.966	.758	.311	.447	-.352	.015	-.289	.643	1	
Zn	.173	-.38	.7	.428	.347	.119	.423	.715	.559	.061	-.49	-.152	-.06	.145	.518	1

N=24
FOR SIGNIFICANCE=0.05, R>= 0.381
FOR SIGNIFICANCE=0.01, R>= 0.487

Table 4-5. The coorelation matrix for element concentrations in stems of sugar maple 2-year olds grown in water culture.

	Al	**B**	**Ba**	**Ca**	**Cu**	**Mg**	**Mn**	**P**	**S**	**Si**	**Zn**
Al	1										
B	.656	1									
Ba	.77	.415	1								
Ca	.57	.396	.718	1							
Cu	.119	.142	.193	-.054	1						
Mg	.269	.203	.398	.346	.114	1					
Mn	.118	.102	.25	-.025	-.042	.348	1				
P	.081	.313	-.126	-.329	.215	.031	.296	1			
S	.099	.415	.161	-.157	.418	.226	.319	.565	1		
Si	.548	.177	.468	.276	-.017	.153	.102	-.108	-.095	1	
Zn	.561	.447	.498	.253	.309	.378	.062	.26	.106	.39	1

N=24

FOR SIGNIFICANCE=0.05, R>= 0.381

FOR SIGNIFICANCE=0.01, R>= 0.487

OTHER SIGNIFICANT STEM COORELATIONS:

ELEMENTS	N	CORRELATION	SIGNIFICANCE
Cr - Al	20	0.529	0.05
Cr - B	20	0.466	0.05
Cr - Ba	20	0.460	0.05
Cr - Zn	20	0.421	0.05
Fe - Al	22	0.760	0.001
Fe - B	22	0.712	0.001
Fe - Ba	22	0.641	0.001
Fe - P	22	0.387	0.05
Fe - Si	22	0.508	0.01
Fe - Zn	22	0.614	0.01
V - Al	20	0.709	0.001
V - B	20	0.553	0.01
V - Ba	20	0.722	0.001
V - Ca	20	0.591	0.01
V - Si	20	0.499	0.05

Table 4-6. The coorelation matrix for element concentrations in stems versus roots of sugar maple 2-year olds grown in water culture.

ELEMENT	COUNT	CORRELATION	R-SQUARED	SIGNIFICANCE
Al	24	0.582	0.339	0.01
B	24	-0.375	0.140	NS
Ba	24	0.266	0.071	NS
Ca	24	0.597	0.357	0.001
Cu	24	0.520	0.271	0.01
Mg	24	0.448	0.201	0.05
Mn	24	0.112	0.013	NS
P	24	0.380	0.144	NS
S	24	0.502	0.252	0.01
Si	24	0.008	0.000	NS
Zn	24	0.449	0.201	NS

NS=not significant

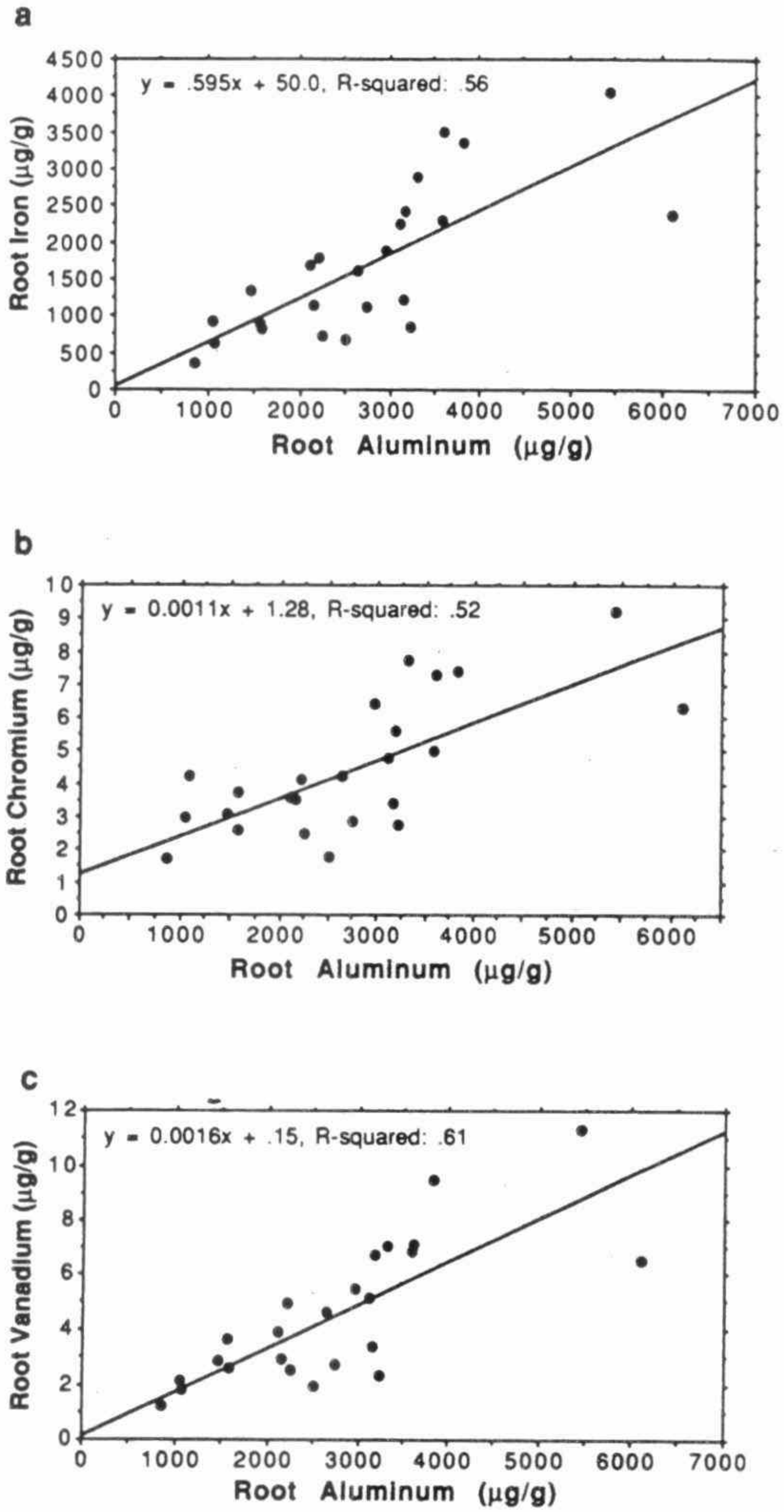


Figure 4-8. Root aluminum versus root iron (a), root chrominum (b), and root vanadium (c) in sugar maple 2-year olds grown in solution culture.

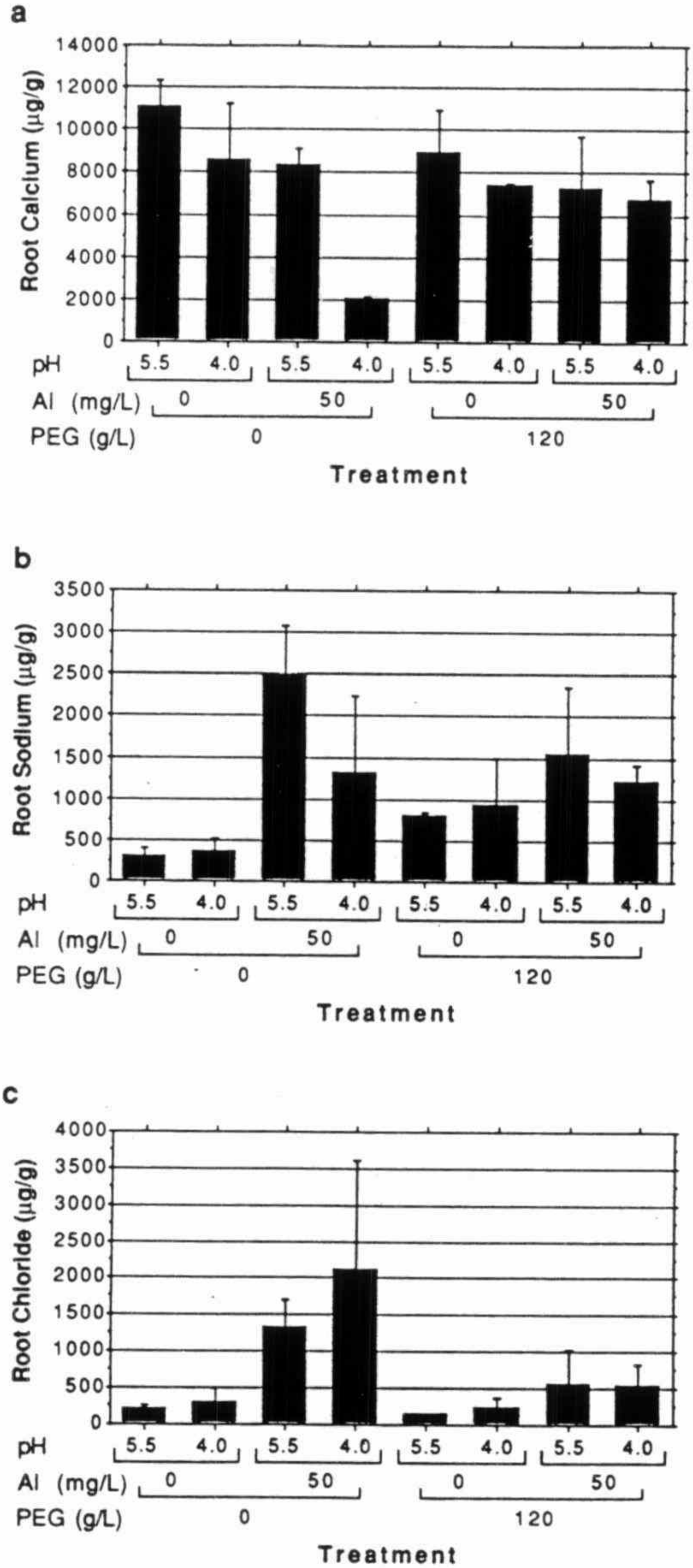


Figure 4-9. The effect of varying pH, aluminum and polyethylene glycol concentration on the root calcium (a), root sodium (b), and root chloride (c) concentrations (+/- one standard deviation) in white spruce seedlings grown in solution culture.

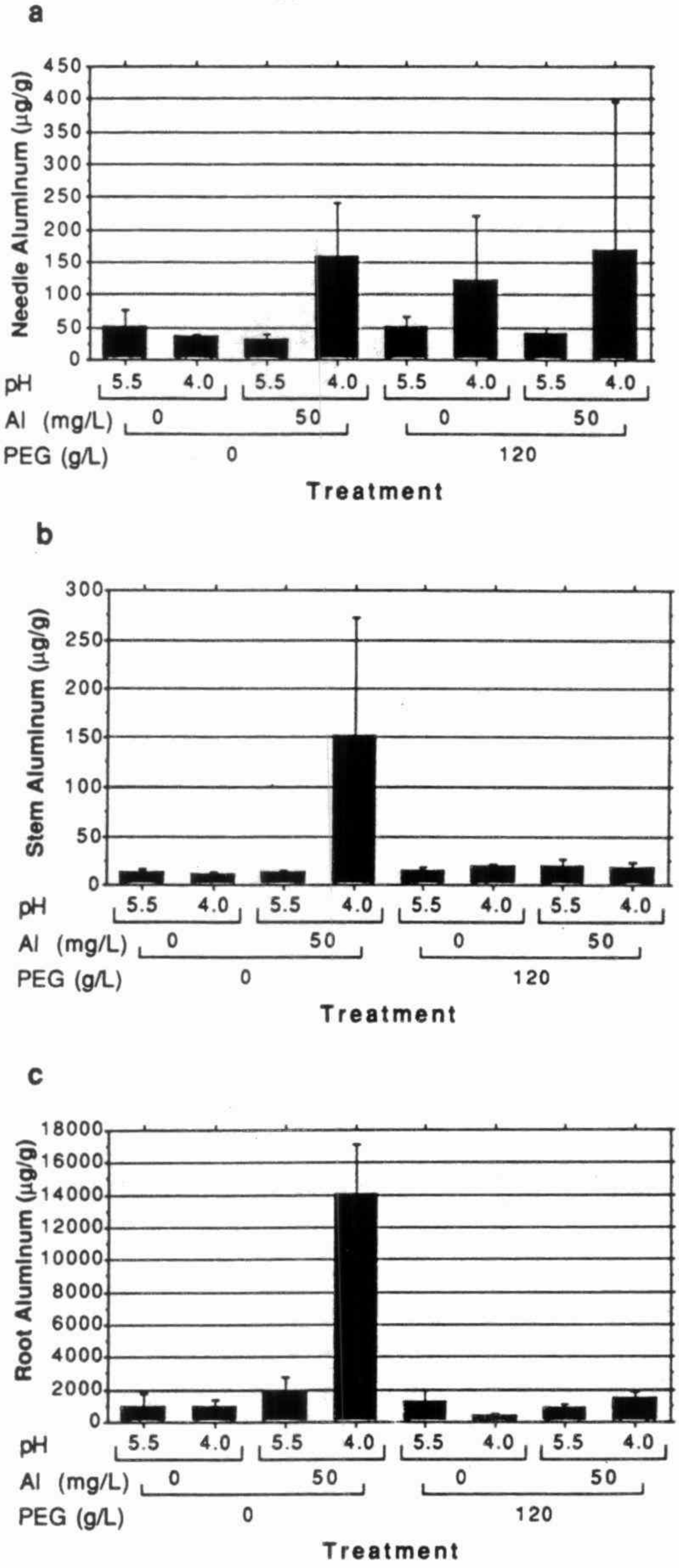


Figure 4-10. The effect of varying pH, aluminum and polyethylene glycol concentration on the needle aluminum (a), stem aluminum (b), and root aluminum (c) concentrations (+/- one standard deviation) in white spruce seedlings grown in solution culture.

Table 4-7. Treatment means of element concentrations with varying polyethyelene glycol concentration, aluminum concentration, and pH for white spruce seedlings grown in water culture.

	PEG (g/L)	Al (mg/L)	pH	root Al	stem Al	needle Al	root Ba	stem Ba	needle Ba	root Ca	stem Ca	needle Ca	root Cl	stem Cl
1	0	0	5.5	968	12.9	52.7	164	135	139.0	11100	4720	13700	221	1000
2	0	0	4.0	1030	11.6	37.3	346	180	243.0	8550	3440	8800	315	1200
3	0	50	5.5	1950	13.9	32.0	•	117	299.0	8310	2530	7810	1330	7960
4	0	50	4.0	14000	152.9	160.1	•	194	203.0	2080	2430	11100	2110	7180
5	120	0	5.5	1310	14.1	52.6	125	133	159.0	8930	6720	14200	157	618
6	120	0	4.0	351	18.9	121.9	185	105	112.0	7390	6030	9040	251	685
7	120	50	5.5	931	19.8	42.3	157	132	96.0	7290	4800	14300	564	2030
8	120	50	4.0	1440	17.8	169.2	•	119	115.0	6720	4210	11100	554	3620

	needle Cl	root Cu	stem Cu	root K	stem K	needle K	root Mg	stem Mg	needle Mg	root Mn	stem Mn	needle Mn	root Na	stem Na
1	1870	49.7	•	2980	9050	13200	3210	2210	3270	238.0	70.8	283	297	760
2	1250	113.0	•	•	10300	10700	3340	1400	2310	257.0	109.0	234	359	223
3	8380	•	•	•	8270	10000	4140	1330	2180	307.0	68.1	214	2490	5490
4	4220	175.0	•	•	8400	9240	4860	1430	3470	71.7	86.7	238	1320	2140
5	1780	•	•	•	4430	11100	2930	1860	2640	176.0	60.4	323	809	1310
6	1180	158.0	•	4060	4170	11000	1620	1760	1540	133.0	80.6	181	944	2310
7	2160	•	6.7	4300	4740	7820	2140	2210	2780	121.0	66.9	257	1540	2300
8	4600	70.3	•	•	4015	10800	2920	1710	3090	175.0	58.3	269	1230	3260

	needle Na	root U	stem U	needle U	root V	stem V	needle V
1	200	.48	•	.45	4.83	.34	.35
2	•	1.68	.70	1.65	4.76	•	.45
3	3670	1.08	.70	1.62	4.02	•	•
4	1040	•	•	.39	3.05	•	•
5	318	.90	.21	.43	6.34	•	•
6	752	.50	.23	.37	4.34	•	.87
7	669	1.79	.67	.30	5.07	•	•
8	1650	1.09	.51	2.61	6.98	•	•

4-7). It is unlikely that this is an experimental artifact and that the membrane interfered with the uptake of these elements since concentrations were similar on both sides of the dialysis membrane (Table 4-1).

In spruce there was a significant correlation between root Al and root Ca concentrations (negative) and between root Na and root Cl concentrations (positive) (Table 4-8, Fig. 4-11). In the stem this relationship became tighter for Na vs Cl and weaker for Al vs Ca (Table 4-9 and 4-10). Only for Cl was there a significant correlation between the stem and the needles of white spruce (Table 4-11).

Our results show that white spruce may be more drought-tolerant than sugar maple and more Al-sensitive if the Al is present at moderately high concentrations.

Table 4-8. The coorelation matrix for element concentrations in roots of white spruce seedlings grown in water culture.

	Al	**Ca**	**Cl**	**Mg**	**Mn**	**Na**	**V**
Al	1						
Ca	-.681	1					
Cl	.401	-.421	1				
Mg	.406	-.196	.642	1			
Mn	-.469	.607	.091	.266	1		
Na	-.009	-.173	.754	.355	.201	1	
V	-.347	.281	-.114	.083	.092	.042	1

N=23 FOR SIGNIFICANCE=0.05, R>= 0.388
FOR SIGNIFICANCE=0.01, R>= 0.496

OTHER SIGNIFICANT ROOT COORELATIONS:

ELEMENTS	N	CORRELATION	SIGNIFICANCE
Cu - Na	12	0.512	0.05
K - Ca	3	-0.906	0.01
K - Cu	2	1.000	0.001
K - Mg	3	0.999	0.001
K - Mn	3	-0.977	0.01
K - Na	3	0.966	0.01

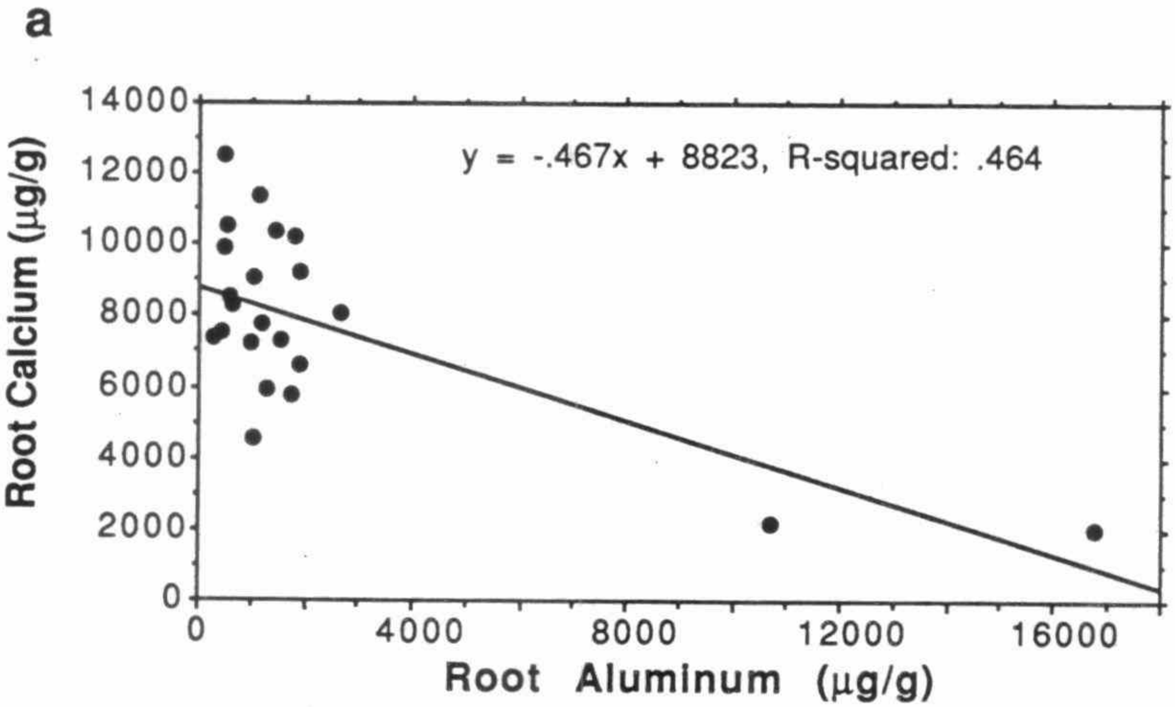


Figure 4-11. Root aluminum versus root calcium in white spruce seedlings grown in solution culture.

Table 4-9. The coorelation matrix for element concentrations in stems of white spruce seedlings grown in water culture.

	Al	**Ca**	**Cl**	**K**	**Mg**	**Mn**	**Na**
Al	1						
Ca	-.259	1					
Cl	.408	-.7	1				
K	.243	-.474	.345	1			
Mg	-.376	.441	-.422	-.029	1		
Mn	.137	-.317	-.097	.143	-.368	1	
Na	.063	-.409	.826	.014	-.219	-.295	1

N=21 FOR SIGNIFICANCE=0.05, R>= 0.388
FOR SIGNIFICANCE=0.01, R>= 0.496

OTHER SIGNIFICANT ROOT COORELATIONS:

ELEMENTS	N	CORRELATION	SIGNIFICANCE
Ba - Al	18	0.456	0.05
Ba - K	17	0.559	0.05
U - Ca	13	-0.706	0.01
U - K	12	0.527	0.05
V - Ca	3	-0.941	0.01

Table 4-10. The coorelation matrix for element concentrations in needles of white spruce seedlings grown in water culture.

	Al	Ca	Cl	K	Mg	Mn
Al	1					
Ca	-.026	1				
Cl	.238	-.514	1			
K	.061	.302	.056	1		
Mg	.572	.106	.226	.236	1	
Mn	.157	.5	-.206	.37	.359	1

N=23 0.05 significance = 0.42

OTHER SIGNIFICANT NEEDLE COORELATIONS:

ELEMENTS	N	CORRELATION	SIGNIFICANCE
Ba - Ca	16	-0.682	0.01
Ba - Cl	16	0.496	0.05
Na - Ba	13	0.573	0.05
Na - Cl	19	0.915	0.001
U - Ba	9	0.619	0.05
V - Al	4	0.962	0.001
V - Ca	4	-0.776	0.05
V - Cl	4	-0.866	0.05
V - Mg	4	-0.948	0.01

hydraulic conductivity varies with matrix potential, creating pronounced wetting fronts in unsaturated soils when wetted from the surface (Armson 1977). Furthermore perched water tables are common in shallow containers, since container walls tend to restrict drainage of water, and the shallow depth contributes to saturation at the bottom which may induce poor aeration in wetter moisture regimes (Spomer 1975). It is also difficult to know the precise water potential at the root surface, since water is continually removed at the root/soil interface of transpiring plants, and water potentials, usually derived from soil moisture release curves and gravimetric moisture content, reflect the entire soil rather than the rhizosphere. Lastly, precise regulation of pH and Al status in an intact soil/plant system is difficult, since the seedlings are anchored in a soil substrate, and are sensitive to mechanical damage when adjusting nutrient status by supplementation and mixing.

There are several experimental advantages in using the PEG culture system. Moisture stress (osmotic potential) is maintained at relatively stable and uniform levels in a flowing nutrient solution circulating the roots. Root water potentials tend to reflect solution potentials because of separation by a thin semipermeable membrane and the continual replenishment of ions near root surfaces. Since the seedlings are raised in liquid medium, pH and Al concentrations are considerably easier to measure and control, and unlike soil-based systems root development can be easily observed in a clear solution and in a flexible, transparent membrane system.

Potential problems with the PEG culture system are that possible toxicity or contamination of PEG may cause undesirable side effects in plants, although several investigators have considered PEG of specific molecular weight (14,000-16,000) to be non penetrating (Williams and Shaykewich 1969, Michel 1971). Selection of highly purified PEG compounds should eliminate the contamination problems of metals (Lawlor 1970). The use of a membrane system to cover roots should overcome PEG toxicity effects because the cellulose dialysis membrane is impermeable to large molecules. However, application may limit stress induction to 16-27 days because of probable membrane degradation (Krizek 1985). We found that two weeks was probably the upper limit for membrane integrity which agreed with other studies indication that reliable moisture stress effects can be achieved in plants in a short time without affecting the passage of water or nutrients to the roots and penetration of PEG into the plant (Kaufman and Eckard 1971).

The system designed for our experiments was based on those described by Tingley and Stockwell (1977) and Orlander and Due (1986). Young seedlings with well developed root systems were suspended in rectangular (15x15x40 cm) root growth chambers constructed from 8 mm opaque plastic. The exterior of the chambers were covered with foil and rubberized duct insulation to minimize solution warming. The chambers contained PEG dissolved in a nutrient solution which was circulated by an electric pump attached to a plastic reservoir standing in a water-bath below the chamber.

The root systems of the seedlings were enclosed at the root collar in one side of a semipermeable membrane pouch of 10 cm diameter seamless dialysis tubing (Spectrapor 1) which was immersed in the culture solution. The tubing was twice as long as the chamber depth, and was folded so that the two open ends extended above the liquid. The ends were clipped to a plastic cross brace which supported the lower stem of the plant. In the liquid, the membranes collapsed against the root mass providing good contact between the plant and solution. The pouch and cross brace were detachable from the chamber to allow periodic inspection of root development. The seedling stem protruded through holes which were aligned with the cross braces in the chamber lid.

2. Problems with the Solution Culture Experiment

a) High Air Temperature: The greenhouse air reached 30 C every sunny day and 40 C on occasion during the first two runs of the solution culture experiment, and this probably served as an additional stress to the sugar maple seedlings. The nutrient solutions were cooled with ice packs and all of the solution holding apparatus were insulated and out of direct sunlight which reduced heating of the solution. However, such high air temperatures can be harmful and have been reported to scorch leaves of sugar maple (Pereira and Kozlowski 1977). The third and forth experiments were in the fall, thus temperatures in the greenhouse seldom exceeded 25 C.

b) Mold and Fungal Growth: Fungus appeared in the growing container 4 to 6 days after the start of every run of the water culture experiment. The growth started around the stem of the seedling on the dialysis membrane surface, which protruded above the water culture solution, and spread to the nutrient solution surface and to some degree to the inside air-exposed surface of the growing container. There appeared to be a second type of fungus growing inside some of the dialysis membranes (among the seedling roots) below the nutrient solution surface. It grew more slowly and was rarer than the above-water type.

These fungi are undesirable because of absorption of nutrients and potential release of toxic compounds into the culture solution. They also accelerate the degradation of the dialysis membrane.

c) Concentration of PEG: In the first experiment the concentration of PEG was 100 g/L of nutrient solution which gave a potential of -2.2. The sugar maple seedlings dessicated rapidly and were crisp within 5 days of exposure. In the second and third experiments with sugar maple PEG was reduced to 25 g/L and gave a theoretical osmotic potential of -0.4 bars. Plants showed much milder symptoms of drought stress. In the fourth experiment white spruce was exposed to a nutrient solution containing 120 g/L of PEG (-3 bars). Once again seedlings survived with some physiological reaction to the drought. These experiments demonstrate the very large difference between sugar maple and white spruce in reaction to drought stress.

d) Rates of Circulation: The solutions were circulated by pumps at 6 L/min when no PEG was present (total 9.5 L of nutrient solution). PEG increased the viscosity of the solution, and slowed the rate of circulation. After the first run the intake holes of the chamber were widened to reduce flow constriction, but the PEG treatments (drought) still had slower circulation rates which may have produced warmer solution temperatures and lower concentrations of dissolved oxygen. Any "drought" effect may have been complicated by these factors.

e) Chemical Precipitation: Particles were found suspended in solution and deposited on the dialysis membrane surfaces and the inside surface of the growth chamber at the end of the experiment. This was more obvious in the treatment without PEG. The solubility of Al is known to be pH specific. At pH 5.5 and at pH 4.0, 98% and 50% of total Al added precipitated to form white aluminum hydroxide. Phosphorus also co-precipitated with the Al. Ninety-eight percent of P at pH 5.5, 88% at pH 4.0, and 10% in the absence of Al had precipitated in solution. A sample of the jelly-like floc contained Al (5 ppm), Na (10 ppm), Cl (39 ppm), and Ca (140 ppm). Under the microscope living rotifers, mites, and protozoa were observed. Adhering soil particles from the seedling roots were the probable source of innoculum. Use of sterile root seedlings may help reduce this problem, but it would result in artificial growing conditions.

f) PEG Inside Membrane: The dialysis membrane can keep PEG from direct contact with the roots. However, once the membrane deteriorates (as found in the first 3 experiments) PEG can penetrate and come in direct contact with the roots. PEG is potentially toxic to plants and contact should be avoided. Using this system in short term experiments should prevent membrane deterioration and thus PEG penetration.

g) Transplanting Stress: In the first two experiments a significant number of the sugar maple seedlings died during the experiment. We hypothesized that the transplanting process, which involved removing seedlings from soil, rinsing roots with distilled water, and weighing plants before they were placed in the membrane and the nutrient solution, was too harsh on these young seedlings. In the third sugar maple experiment we used 2-year old trees which were bud-broken in nutrient solution. This approach reduced handling and transplanting shock but not completely, since leaves drooped for a few days from the start of the experiment, recovering later in the control treatment. Shoots did not grow appreciably during the experiment, although we noticed a slight increase in root biomass.

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A sample of the soil was used to test chemical and physical properties. The soil was leached in columns over a 24-h period with deionized water adjusted to the four treatment pHs (5.5, 4.5, 3.5, and 2.5). This leachate was collected, filtered, and analyzed for P, K, Ca, Mg, Al, and Mn using the methods described for plant analysis.

A preliminary experiment was run to determine the drought treatments. It was observed that the soil dried out quickly and needed watering every two or three days depending on the amount of drainage and evaporation. Both drought symptoms and oversaturation of soil were avoided when approximately 90 mL of water distributed evenly over the period of a week was added to the growing seedlings.

The soil is classified by the Canadian system of soil classification as a humic gleysol. Below the litter was a dark highly organic B horizon that ranged from 10-25 cm which was followed by a brown Cg horizon, which exhibited slight gleying and saturation with water between 50 and 100 cm of the surface.

Sugar maple (*Acer saccharum* Marsh.) seeds were obtained from the seed bank of the Canadian Forestry Services National Tree Seed Center in Petawawa. The seeds were collected in Denbigh, Ontario from a parent tree in 1984. They were stratified in damp peat moss and refrigerated at 2-4 C for approximately 2-3 months.

Germinated seeds were planted directly into the collected soil. The seedlings were allowed to grow for about 1 month (June) prior to the beginning of the experiment. During this period the seedlings were watered about 3 times per week with tap water (overhead sprinkling), and received supplemental overhead lighting to extend the growing period to 12 hours.

The experimental set up included 12 treatments, with 12 seedlings per treatment (total of 144 seedlings), 4 blocks with 3 pots per treatment per block. There were 4 pH treatments--5.5, 4.5, 3.5, and 2.5; and three moisture regimes--a control, an intermediate drought, and a severe drought. The seedlings were located randomly in these blocks and rotated weekly to reduce edge effects. The seedlings were raised under shade frames simulating forest conditions of a true canopy.

The pH of deionized water was adjusted to the various treatment pHs using a 2:1 H_2SO_4:HNO_3 ratio, which is similar to the acid ratio found in precipitation in south-central Ontario. Sodium hydroxide (NaOH) was used to increase the pH of the solution as needed.

Drought treatments were based on the soil water holding capacity and experience from previous experiments. The control of the moisture regimes was watered 3 times weekly with 30 mL of water, the intermediate drought received 45 mL every 3 to 4 days and the severe drought received 60 mL every 4 to 5 days. Each pot received a total of 180 mL over a 10 day cycle.

To maintain a constant moisture stress, fixed intervals between water addition (noted above) were used. Differences in soil water potential and transpiration rates between seedlings were minimized by thoroughly mixing the soil. Individual seedlings were selected for uniformity in size at the start of treatment.

After four weeks of treatment (28 days) seedlings were measured for height and harvested by block in a two day period. The seedlings were rinsed in tap water to remove soil particles from the roots, and root and shoot area was measured using a rhizometer. The seedlings were then over dried at 60 C for a minimum of 24 hours; dry weights were obtained using a Sartorius #1712 balance. Samples were ground by a Wiley Mill with a 2 mm mesh and stored in polyethylene vials.

The samples were analyzed for Al, Mn, Cl, and Na using Instrumental Neutron Activation Analysis (INAA). They were irradiated using the SLOWPOKE (Safe Low Powered Critical Experiment) research reactor at the University of Toronto, and the samples were counted on a Gamma Ray Spectrometry System (Canaberra Ind. #8180, Multichannel Analyzer). Samples were irradiated for 1 minute at 2, 5, and 10 Kw, and counted for 300 seconds after a decay of 7 minutes. The principles of INAA are outlined by Meucke (1980) and the calculations of concentrations is detailed by Havas (1980).

Plant K, Ca, and Mg were determined by Atomic Absorption Analysis. Samples were digested using a solution composed of 30% H_2O_2, Se powder, Li_2SO_4 H_2O and H_2SO_4. Samples were digested at 380 C for 2 hours and diluted to 50 mL with deionized water. All digestions were analyzed within 48 hours of digestion completion. Standards for K and Mg analysis were diluted with a 30% $LaCl_2$ solution to supress ionization and increase absorbance, and samples for Ca determination were diluted with deionized water. Standard reference solutions were prepared from certified atomic absorption stock solutions. Standards were checked every 5 samples. Plant Phosphorus, in the digested samples, was determined colorimetrically by the molydbdenum blue method using stannous chloride as a reducing agent (Allen, 1974). Total N was determined by Kjedahl digestion and distillation using boric acid as a reagent (Allen 1974).

Appendix 2: Sponge/Sand Experiment--Method

Sugar maple seeds were obtained from the same source as the soil experiment. The seeds were soaked overnight in distilled water at room temperature. The seedcoat was removed to reduce germination time (this was not done in the soil experiment) and stratified in damp peat moss at low temperature for about 2 months. Seedlings were planted directly into the sand/sponge media.

The inert media for growing the plants consisted of silica sand (1 part grade 10, 4 parts grade 24, 4 parts grade 48, and 4 parts F grade pure silica) and shredded pure cellulose sponge. The silica sand is a well known inert media which poses problems of poor root penetration and low water retention. Hence another inert material was needed to reduce compaction and increase water retention. We saturated perlite, vermiculite, rock wool, and shredded cellulose for 48 hours with deionized water at pH 2.5, the lowest pH, to check possible metal and nutrient contamination of the media. The leachate was analyzed using Inductively Coupled Plasma (ICP) using the methods described in the soil experiment. The shredded cellulose sponge released the lowest levels of impurities. Hence sand and sponge were mixed in a 13:8 ratio and acid washed and rinsed until leachate pH from the medium did not change.

There were 3 pH treatments (control=5.5, 4.5, and 3.5), 3 drought treatments (control, intermediate, and severe), and 4 Al addition treatments (control=0, 20, 100, and 250 mg/L) for a total of 36 treatments; with 12 seedlings per treatment (total of 432 seedlings).

The drought treatments were based on moisture retention values from levels in soils described in the literature. The control water level was held between 70 and 100%, intermediate drought between 50 and 70%, and the severe drought between 30 and 50%.

Water content of the inert media was controlled gravimetrically. Six sample pots from each drought treatment were weighed every few days and water was added when needed (i.e. when low end of the percent water limit was reached, 30% for the severe drought treatment).

Treatment Al concentrations were based on concentrations deemed harmful to plant growth (Magistad, 1925), from concentrations found in south-central Ontario soils (Bozic, pers. comm.), and from values obtained for leachate Al of the soil experiment. The Al was added to the sand culture to mimic soil solution Al at different pH. A stock Al solution was made using deionized water and $Al_2(SO_4)_3$. The pH was adjusted as in the soil experiment prior to application. Volumes of 20 mL of each solution were applied to the medium at intervals prescribed by the drought treatments.

Nutrients were supplied separately during the experimental period. Ingestad solution (1962) was used at a concentration fo 100 mg/L N, and was applied once per week to every seedling.

Each seedling received 20 mL of nutrient solution and 20 mL of Al solution per week regardless of treatment. Control treatments received up to 10 mL more water. After one month of treatment, the seedlings were harvested and analyzed as in the soil experiment.

Appendix 3: Solution Culture Experiment--Method

The set-up for growing seedlings in water culture consisted of a rectangular box with a removable two-piece lid connected by tubing to a pump which circulates the nutrient solution. The rectangular box (growing container and split lid, were made of a hard, black, inert plastic. The split lid had 6 holes drilled at the center joint to hold seedlings at the seam. The inside rim of the growing container had six pairs of vertical slots (six on each side, directly opposite from one another) to hold plastic cross-braces which suspended the seedlings in the container and flowing nutrient solution.

The growth container had a flow inlet, located near a bottom corner of one end of the container, and a flow outlet, located in the opposite top corner of the container below the solution surface. The inlet and outlet consisted of 3-4 cm of clear plastic connector for attaching flexible tubing. Attached to the inlet inside the growing container was a long green plastic tube with holes down its length and plugged at the unconnected end with a rubber cork stopper, which helped to distribute the solution more evenly throughout the container. The outlet of the growth chamber had a short piece (2 cm) of flexible Nalgene tubing (Nalge 8000, 1/4 inch inside diameter, 3/32 inch wall thickness) which were angled downward to avoid air intake.

The pump inflow and outflow were connected to the growth chamber by Nalgene tubing. The pumps (201 FLUVAL aquarium pumps) produced a rate of flow of 360 L per hour or 6 L per minute with water. The pump is of plastic construction, with a reservoir/mixing chamber, and can be completely dismantled for cleaning. The pump and growth chamber combined hold about 9.5 L of solution.

The pump was set in a cooler filled partially with water and ice packs (which were changed daily). The growth chamber and tubing connecting the pump and container were insulated with pipe insulation and duct tape for cooling.

To impose drought, polyethylene glycol (PEG, Carbowax, molecular weight 15,000-20,000) obtained from Fisher and Union Carbide was added to the water culture. The PEG was gradually dissolved in 10 L batches of nutrient solution, in a large plastic container with constant stirring. The stirring was slow enough to prevent solution frothing.

To prevent the potentially toxic PEG from reaching the seedling roots, the roots were enclosed in a semi-permeable dialysis membrane (Spectra/Por 1) which allow penetration of molecules smaller than 8,000 molecular weight.

The membrane was purchased in tubular form. The plant roots were inserted in one end of the membrane tube and the tube was folded and clipped to the plastic cross-braces, making sure that both ends of the tube remained above the surface of the nutrient solution. This ensured that the nutrient solution could pass only through the membrane. The membrane tube was long enough to permit circulation between the bottom of the membrane and the base of the container.

Seedling Preparation

Sugar maple seeds, obtained from the Canadian Forest Service (lot 8630181, from Vineland, Ontario), were placed in a tray and covered with a thin layer of peat moss and sand. Seeds were watered, covered and kept at 10 C on April 9, 1987. During the last two weeks in May 1987, the trays were moved outside and seedlings were transplanted into a combination of fertilized greenhouse soil and peat moss. The seedlings were watered and kept outside until use.

Membrane Permeability

The permeability of the dialysis membrane to Al, macronutrients, PEG and dissolved oxygen was tested. Empty membranes, held open by pieces of inert plastic, were placed in two treatments, both with a base of nutrient solution and Al with PEG and without PEG. The solutions were allowed to seep into the membrane. After 48 hours samples were collected from inside and outside of the membrane. The samples were analyzed using Neutron Activation Analysis.

First Sugar Maple Experiment

The first experiment ran for 12 days (June 25 to July 7 1987). There were eight treatments consisting of two concentrations of Al (0 and 50 mg/L) added as $AlCl_3.6H_2O$, two concentrations of PEG (0 and 100 g/L), and two pHs (5.5 and 4.0). There were six plants per treatment. The PEG concentration was based on preliminary work with conifers in the same system. The base nutrient solution was identical to Ingestadt (1971) for birch seedlings, with stock solutions B and C diluted to give a final nitrogen concentration of 125 mg/L. Sodium hydroxide and hydrochloric acid were used to adjust and keep the pH constant.

Forty-eight sugar maple seedlings (from above) were removed from soil culture, their roots were rinsed with distilled water and were put into dialysis membranes and submerged into the different treatments with the roots in the nutrient solution and the stems extending through the holes in the center of the lids. Wet weight of seedlings was measured at the beginning and at the end of the experiment; observations on growth were recorded. Seedlings were grown under natural light in the greenhouse.

Second Sugar Maple Experiment

This experiment was performed between August 12 and 26, 1987 (14 days). The set-up was as before except for the following:

(1) A new nutrient solution, based on Ingestadt 1962, was used. It was similar to the previous nutrient solution, but with

relatively higher concentrations of P, Ca, and K compared to the N concentration.

(2) The circulation in each box was improved by increasing the size of the holes in the green plastic tube connected to the inlet tube inside the box.

(3) The seedlings were older (3 months) and were put into nutrient solution 24 hours before the experiment began, allowing time to adjust to transplanting.

(4) The PEG concentration was reduced to 25 g/L.

(5) Wet weight, dry weight, and elemental composition using Neutron Activation Analysis were recorded.

Third Sugar Maple Experiment

This experiment was conducted during March 2-16, 1988 (14 days). The set up was the same as in experiment two except for the following:

(1) Two-year old sugar maples were used. They were obtained from W. Richardson Farms, Ltd., in Pontypool, Ontario on November 19, 1987. They were wrapped in moist cloth in a cold room (temperature 2-7 C) until required, then brought out and placed in CAN-AM containers. The CAN-AM containers were put in a tub filled with Ingestadt (1971) nutrient solution, and bud-broken at 25 C under a 16:8 hour light/dark photoperiod.

(2) Plants were exposed to natural and artificial light with a photoperiod of 16:8 light to dark.

(3) The tree roots were cut to equal length.

(4) The seedlings were bud-broken in water culture prior to the experiment, minimizing transplant shock and handling.

(5) Only three plants per treatment were used (reduced from six since plants were larger).

(6) The air temperature was lower (due to colder temperatures outside). Thus insulation was not put on the tubing connecting the growing container and the pump.

(7) Samples were analyzed using Inductively Coupled Plasma Emission of dried, ground, and nitric acid digested material.

First Experiment with White Spruce

This experiment ran from October 5-29, 1987 (21 days). The set-up was identical to the second experiment with the following alterations:

(1) White spruce seedlings (one year old) were used instead of sugar maple.

(2) The PEG concentration was 120 g/L.

Appendix 4: Soil Experiment--Results

PART a. ELEMENT CONCENTRATIONS IN ROOTS (UNLABELLED ELEMENTS) AND SHOOTS

PART b. GROWTH DATA

LEGEND

D1 = CONTROL DROUGHT

D2 = INTERMEDIATE DROUGHT

D3 = SEVERE DROUGHT

ALL CONCENTRATIONS IN µg/g

a.

	pH	drought	N	P	K	Ca	Mg	Cl	Na	units	Al	Mn	Shoot-N	Shoot-P	Shoot-K	Shoot-Ca	Shoot-Mg	Shoot-Mn	Shoot-Al	Shoot-Cl
1	5.5	D1	26600	1100.0	4375.0	•	687.5	1648	1146	a	7745	964.2	26425	762.5	4312.5	7937.5	1375.0	4086.2	448.7	1828.0
2	5.5	D1	30131	1026.0	6200.0	3135.7	1282.7	1222	940	a	6947	1452.6	23625	600.0	5937.5	8062.5	1062.5	5424.9	260.5	1493.1
3	5.5	D1	25900	1350.0	4562.5	•	687.5	1420	2024	a	11794	1287.0	26775	787.5	5062.5	7187.5	1500.0	3867.7	288.1	1813.1
4	5.5	D1	25025	1300.0	4625.0	2625.0	875.0	729	1778	a	5127	1386.6	26950	650.0	5562.5	8562.5	1687.5	4121.0	204.6	1652.8
5	5.5	D2	26775	1137.5	4937.5	2750.0	1062.5	620	1098	b	7409	1145.8	28875	625.0	6187.5	7687.5	1125.0	3834.9	474.9	1518.2
6	5.5	D2	22750	1075.0	7125.0	62.5	1000.0	1759	3194	b	7316	1605.9	27475	700.0	5500.0	8125.0	1500.0	4649.3	189.7	1460.9
7	5.5	D2	23625	975.0	5062.5	•	937.5	1500	1518	b	4362	960.1	23450	700.0	4437.5	8500.0	1500.0	4896.4	227.5	1218.0
8	5.5	D2	25550	1100.0	5750.0	2562.5	1062.5	1105	1244	b	6612	1327.7	30100	712.5	4875.0	8000.0	1500.0	4132.5	228.1	1578.9
9	5.5	D3	25550	1037.5	5937.5	2937.5	1312.5	1493	1290	c	6332	1381.9	25725	662.5	5375.0	9375.0	1750.0	5382.4	114.3	1685.1
10	5.5	D3	27727	868.0	6511.0	1695.6	746.0	1330	1245	c	6203	1638.6	26950	675.0	6750.0	9125.0	1250.0	2829.4	123.4	760.4
11	5.5	D3	26075	1037.5	5000.0	•	625.0	1286	1064	c	6165	962.1	26600	775.0	5250.0	7000.0	1500.0	4539.4	161.9	1905.1
12	5.5	D3	24150	1175.0	6375.0	•	750.0	1342	1558	c	8106	990.8	24150	787.5	4562.5	5875.0	1250.0	4055.5	226.2	1159.5
13	4.5	D1	24150	1162.5	5375.0	2937.5	1125.0	1699	1550	d	8191	1376.8	26950	675.0	5625.0	8937.5	1812.5	4633.1	307.9	2043.5
14	4.5	D1	28350	1175.0	4687.5	•	937.5	1558	1049	d	6047	1166.2	28000	750.0	6250.0	7687.5	1562.5	4263.8	239.1	3755.6
15	4.5	D1	26950	1050.0	5000.0	2062.5	562.5	1001	1579	d	8047	1378.9	23450	575.0	5562.5	8312.5	1187.5	4805.6	258.2	1611.7
16	4.5	D1	25725	1150.0	5875.0	2500.0	687.5	988	1893	d	8972	1384.2	25900	637.5	5187.5	6812.5	937.5	4291.0	221.8	1534.9
17	4.5	D2	26425	1025.0	5000.0	2375.0	562.5	1243	1563	e	8357	1172.8	26425	637.5	5062.5	7125.0	875.0	2837.6	147.2	1266.9
18	4.5	D2	21525	1112.5	5437.5	312.5	812.5	1275	1511	e	7340	1290.2	28175	750.0	6312.5	8750.0	1625.0	4614.8	256.6	2577.0
19	4.5	D2	21175	900.0	5125.0	•	875.0	1545	1802	e	8098	1224.2	20675	562.5	4687.5	9812.5	1625.0	4879.6	187.5	1892.6
20	4.5	D2	15050	1112.5	4437.5	•	687.5	784	1612	e	10081	1381.5	25725	500.0	5187.5	5437.5	1187.5	3967.7	168.6	1882.5
21	4.5	D3	18725	787.5	4937.5	2062.5	625.0	1800	914	f	4480	935.4	26600	675.0	5750.0	8687.5	1750.0	3594.8	206.9	1421.8
22	4.5	D3	25900	1050.0	5750.0	2187.5	625.0	1203	1374	f	8680	1396.7	24325	600.0	5812.5	7062.5	937.5	4032.4	210.8	1611.4
23	4.5	D3	27300	1000.0	5687.5	2000.0	625.0	1353	1148	f	6944	1374.9	30275	637.5	5562.5	8875.0	1937.5	4365.0	•	1188.0
24	4.5	D3	25025	950.0	6312.5	•	875.0	1233	1166	f	7175	1735.9	25375	650.0	6562.5	8375.0	1437.5	5792.6	233.2	1614.8
25	3.5	D1	25550	1112.5	5250.0	2250.0	750.0	1254	1435	g	9644	1472.7	23625	550.0	5687.5	8625.0	1250.0	4570.0	171.6	1853.9
26	3.5	D1	29400	1087.5	5250.0	1875.0	562.5	1099	2137	g	10043	1165.2	23975	562.5	5500.0	6000.0	875.0	4080.2	199.2	1940.4
27	3.5	D1	25375	1337.5	4812.5	2562.5	875.0	1164	1755	g	11270	1426.4	28700	637.5	6437.5	9125.0	1812.5	4288.9	287.8	1982.0
28	3.5	D1	25025	1237.5	4375.0	2562.5	312.5	1252	2720	g	14849	1455.7	30450	637.5	5187.5	8973.5	1812.5	•	•	•
29	3.5	D2	29575	1087.5	4625.0	•	562.5	1300	1630	h	11998	1263.9	29050	525.0	4312.5	7875.0	1500.0	4260.3	375.2	1531.3
30	3.5	D2	29437	986.0	6235.5	2610.2	870.0	966	1464	h	7435	1498.0	28525	600.0	7562.5	9937.5	1687.5	4668.8	245.5	2306.8
31	3.5	D2	26923	832.8	5526.9	•	1211.4	2314	2128	h	5830	1383.6	27650	575.0	5562.5	912.5	1625.0	4382.3	250.7	2569.6
32	3.5	D2	29400	987.5	6000.0	2500.0	1437.5	1635	1541	h	6296	1310.2	30450	587.5	5125.0	8875.0	1687.5	3896.4	208.8	2727.1
33	3.5	D3	25725	925.0	5062.5	2562.5	1187.5	1831	1298	i	6776	1270.3	27475	575.0	5000.0	9437.5	2000.0	4307.8	161.9	1262.9
34	3.5	D3	23450	837.5	5812.5	•	1000.0	1433	1091	i	5991	1202.5	24670	550.0	5187.5	9500.0	1625.0	5460.6	214.9	2042.1
35	3.5	D3	28806	1067.0	5801.4	3326.0	1624.3	1387	1190	i	8012	1363.7	30625	600.0	6000.0	9000.0	1312.5	4086.4	235.7	2249.5
36	3.5	D3	21525	925.0	5812.5	•	875.0	1496	1484	i	7823	1367.5	22400	587.5	4875.0	6625.0	1125.0	3924.7	304.8	838.1
37	2.5	D1	24722	1164.0	5752.0	2946.0	1473.0	1179	1439	j	9761	1271.5	26425	637.5	6187.5	7312.5	1687.5	4380.1	242.6	1686.5
38	2.5	D1	26950	1000.0	4875.0	•	750.0	1252	1731	j	8327	1158.3	26250	650.0	5250.0	6062.5	1250.0	5285.8	238.9	1761.7
39	2.5	D1	25725	937.5	5687.5	2437.5	687.5	1124	1272	j	6294	1029.5	26250	600.0	5437.5	9000.0	1812.5	3576.3	364.2	1768.5
40	2.5	D1	26075	800.0	6375.0	2312.5	875.0	1516	1092	j	4793	1061.7	24736	612.0	5217.0	8138.5	1808.5	3993.0	310.8	1997.7
41	2.5	D2	27475	1975.0	5437.5	2312.5	937.5	2082	1584	k	•	•	26250	1100.0	6250.0	7750.0	1687.5	4258.2	233.1	1736.3
42	2.5	D2	26075	875.0	6687.5	2437.5	750.0	1283	1588	k	5681	1387.6	29750	650.0	4812.5	9562.5	1937.5	4292.5	177.2	1987.6
43	2.5	D2	26075	962.5	6437.5	2687.5	1437.5	1593	1539	k	7040	1275.6	20475	637.5	6312.5	9000.0	2125.0	5577.5	195.8	1875.5
44	2.5	D2	26600	962.5	5437.5	2750.0	562.5	1799	1579	k	6803	995.7	30275	650.0	5625.0	7937.5	1250.0	3624.4	267.2	1677.9
45	2.5	D3	25550	1075.0	6375.0	•	937.5	934	1774	l	8222	1711.5	22575	562.5	6187.5	7375.0	1375.0	5457.8	•	1829.1
46	2.5	D3	26729	875.0	6087.4	•	968.4	1142	1575	l	7943	1184.2	25200	675.0	6250.0	7750.0	1500.0	4234.0	247.0	3284.1
47	2.5	D3	30625	1162.5	5125.0	3000.0	1062.5	1163	2369	l	9798	1351.8	27300	637.5	5750.0	7000.0	1062.5	805.0	295.9	1619.9
48	2.5	D3	26600	900.0	6500.0	2312.5	687.5	1661	1576	l	6310	1247.2	28175	637.5	5187.5	8750.0	1312.5	4692.7	338.2	1841.4

	pH	drought	root area	shoot area	root wt	shoot wt	repl	samples	Ht	shoot/root wt. ratio
1	5.5	D1	6.00	13.25	.06370	.27820	1	1	88	4.37
2	5.5	D1	7.25	33.00	.08400	.18640	1	2	78	2.22
3	5.5	D1	7.00	39.75	.11780	.26040	1	3	78	2.21
4	5.5	D1	10.75	4.50	.12960	.22460	2	1	68	1.73
5	5.5	D1	3.75	20.25	.04540	.14040	2	2	47	3.09
6	5.5	D1	4.00	24.00	.03780	.15470	2	3	63	4.09
7	5.5	D1	6.00	28.50	.07890	.19740	3	1	63	2.50
8	5.5	D1	7.25	30.50	.09570	.27620	3	2	71	2.89
9	5.5	D1	8.50	25.25	.09770	.28480	3	3	75	2.92
10	5.5	D1	12.25	50.75	.22810	.33410	4	1	71	1.46
11	5.5	D1	15.25	36.00	.13720	.22610	4	2	81	1.65
12	5.5	D1	9.00	58.25	.09970	.36330	4	3	73	3.64
13	5.5	D2	3.75	32.25	.06000	.20550	1	1	78	3.43
14	5.5	D2	10.50	55.25	.16770	.34610	1	2	90	2.06
15	5.5	D2	9.00	43.25	.12370	.26690	1	3	82	2.16
16	5.5	D2	6.50	25.75	.07510	.16878	2	1	54	2.25
17	5.5	D2	10.00	43.75	.18490	.29020	2	2	62	1.57
18	5.5	D2	3.25	18.50	.04350	.14830	2	3	48	3.41
19	5.5	D2	6.25	42.00	.11140	.22790	3	1	70	2.05
20	5.5	D2	5.50	39.50	.11060	.19370	3	2	70	1.75
21	5.5	D2	11.25	39.50	.23810	.30460	3	3	67	1.28
22	5.5	D2	14.00	45.25	.18520	.29950	4	1	73	1.62
23	5.5	D2	11.00	43.50	.15600	.27610	4	2	81	1.77
24	5.5	D2	10.50	12.75	.08170	.11120	4	3	76	1.36
25	5.5	D3	9.25	45.75	.14170	.26080	1	1	86	1.84
26	5.5	D3	11.50	52.00	.17870	.36630	1	2	101	2.05
27	5.5	D3	9.75	46.25	.13070	.28550	1	3	84	2.18
28	5.5	D3	5.50	31.25	.08760	.19730	2	1	50	2.25
29	5.5	D3	6.00	29.75	.09320	.16530	2	2	54	1.77
30	5.5	D3	5.00	20.75	.04270	.11730	2	3	56	2.75
31	5.5	D3	6.50	33.50	.11840	.19070	3	1	69	1.61
32	5.5	D3	10.00	42.50	.20740	.11530	3	2	64	.56
33	5.5	D3	6.50	25.25	.07240	.14920	3	3	69	2.06
34	5.5	D3	9.00	34.25	.12650	.20260	4	1	72	1.60
35	5.5	D3	8.25	34.00	.23120	.13880	4	2	71	.60
36	5.5	D3	12.75	26.50	.18210	.20470	4	3	72	1.12
37	4.5	D1	11.00	44.00	.15100	.30640	1	1	82	2.03
38	4.5	D1	11.00	49.00	.11320	.30360	1	2	82	2.68
39	4.5	D1	6.50	36.00	.17080	.33910	1	3	86	1.99
40	4.5	D1	6.50	28.75	.09350	.14150	2	1	59	1.51
41	4.5	D1	5.25	28.00	.07340	.17210	2	2	63	2.34
42	4.5	D1	7.75	24.50	.08050	.15160	2	3	60	1.88
43	4.5	D1	3.50	26.50	.07850	.16620	3	1	67	2.12
44	4.5	D1	10.50	44.00	.11880	.25660	3	2	65	2.16
45	4.5	D1	7.00	30.50	.11700	.20970	3	3	67	1.79
46	4.5	D1	8.00	40.25	.10360	.25790	4	1	73	2.49
47	4.5	D1	10.75	42.50	.17520	.27580	4	2	72	1.57
48	4.5	D1	11.00	65.00	.13050	.40320	4	3	75	3.09
49	4.5	D2	6.25	.25	.10860	.11900	1	1	81	1.10
50	4.5	D2	9.75	42.50	.19480	.29500	1	2	83	1.51
51	4.5	D2	7.00	52.50	.13390	.33280	1	3	82	2.49
52	4.5	D2	8.00	35.25	.17040	.22320	2	1	62	1.31
53	4.5	D2	9.00	30.25	.10760	.20760	2	2	61	1.93
54	4.5	D2	5.25	31.00	.09490	.18570	2	3	67	1.96
55	4.5	D2	13.00	29.25	.11030	.18760	3	1	66	1.70
56	4.5	D2	5.00	24.50	.08960	.14170	3	2	67	1.58
57	4.5	D2	11.50	27.00	.06360	.16400	3	3	66	2.58
58	4.5	D2	5.25	18.25	.07830	.12640	4	1	72	1.61
59	4.5	D2	10.00	29.25	.12090	.18150	4	2	72	1.50
60	4.5	D2	11.25	57.25	.16680	.36740	4	3	72	2.20
61	4.5	D3	12.00	48.75	.06640	.24190	1	1	100	3.64
62	4.5	D3	8.25	72.25	.13280	.43620	1	2	88	3.28

b.

	pH	drought	root area	shoot area	root wt	shoot wt	repl	samples	Ht	shoot/root wt. ratio
63	4.5	D3	7.50	44.00	.18470	.29540	1	3	86	1.60
64	4.5	D3	7.00	49.75	.11720	.30260	2	1	57	2.58
65	4.5	D3	10.25	13.50	.15290	.15400	2	2	67	1.01
66	4.5	D3	7.50	45.25	.11790	.30350	2	3	64	2.57
67	4.5	D3	8.75	29.75	.11200	.17980	3	1	71	1.61
68	4.5	D3	9.00	49.75	.16890	.30660	3	2	68	1.82
69	4.5	D3	7.75	30.75	.06000	.19890	3	3	67	3.31
70	4.5	D3	13.25	44.75	.15860	.25780	4	1	80	1.63
71	4.5	D3	4.00	26.00	.05240	.15480	4	2	74	2.95
72	4.5	D3	11.50	59.00	.16750	.37260	4	3	74	2.22
73	3.5	D1	9.50	45.50	.18590	.43550	1	1	82	2.34
74	3.5	D1	7.50	41.00	.09830	.29260	1	2	83	2.98
75	3.5	D1	4.75	42.50	.08190	.28150	1	3	95	3.44
76	3.5	D1	6.50	31.00	.10430	.19110	2	1	56	1.83
77	3.5	D1	3.75	31.00	.05640	.19700	2	2	57	3.49
78	3.5	D1	6.75	17.75	.08790	.13010	2	3	56	1.48
79	3.5	D1	6.00	35.50	.08460	.20100	3	1	68	2.38
80	3.5	D1	8.75	36.75	.12670	.22740	3	2	64	1.79
81	3.5	D1	5.00	51.50	.11740	.32220	3	3	68	2.74
82	3.5	D1	11.00	43.00	.12170	.29270	4	1	76	2.41
83	3.5	D1	7.00	36.00	.09210	.21280	4	2	71	2.31
84	3.5	D1	10.50	34.25	.10540	.19920	4	3	75	1.89
85	3.5	D2	8.25	38.00	.14440	.25070	1	1	79	1.74
86	3.5	D2	5.50	34.00	.07570	.20530	1	2	86	2.71
87	3.5	D2	8.00	31.50	.13910	.24930	1	3	81	1.79
88	3.5	D2	6.50	22.50	.08170	.13650	2	1	56	1.67
89	3.5	D2	4.50	27.50	.05650	.17650	2	2	56	3.12
90	3.5	D2	5.75	30.00	.06580	.17400	2	3	54	2.64
91	3.5	D2	3.75	10.00	.05860	.09160	3	1	68	1.56
92	3.5	D2	5.00	26.00	.06380	.13560	3	2	64	2.13
93	3.5	D2	4.25	26.25	.08770	.15790	3	3	64	1.80
94	3.5	D2	4.75	17.75	.04610	.17000	4	1	77	3.69
95	3.5	D2	12.50	56.00	.17460	.37420	4	2	84	2.14
96	3.5	D2	4.75	30.50	.04980	.12000	4	3	74	2.41
97	3.5	D3	8.50	30.25	.14000	.26830	1	1	81	1.92
98	3.5	D3	7.25	46.50	.15990	.36760	1	2	83	2.30
99	3.5	D3	9.00	34.75	.14070	.20380	1	3	86	1.45
100	3.5	D3	6.00	31.25	.13680	.18580	2	1	57	1.36
101	3.5	D3	8.00	34.25	.09770	.19970	2	2	55	2.04
102	3.5	D3	4.00	14.00	.13130	.22270	2	3	55	1.70
103	3.5	D3	8.50	46.00	.09490	.21650	3	1	66	2.28
104	3.5	D3	6.00	29.00	.06630	.16630	3	2	68	2.51
105	3.5	D3	14.00	38.25	.03600	.09840	3	3	68	2.73
106	3.5	D3	7.00	34.25	.12700	.26960	4	1	80	2.12
107	3.5	D3	15.50	41.25	.25390	.28060	4	2	72	1.11
108	3.5	D3	7.50	25.00	.10300	.17030	4	3	72	1.65
109	2.5	D1	8.50	45.25	.10960	.20600	1	1	86	1.88
110	2.5	D1	7.00	19.25	.07350	.17050	1	2	98	2.32
111	2.5	D1	7.00	58.75	.11110	.35110	1	3	76	3.16
112	2.5	D1	9.50	47.00	.12290	.28770	2	1	65	2.34
113	2.5	D1	9.75	67.25	.12500	.18840	2	2	49	1.51
114	2.5	D1	2.75	25.75	.07340	.14330	2	3	61	1.95
115	2.5	D1	9.00	36.25	.11490	.22800	3	1	68	1.98
116	2.5	D1	20.00	46.00	.13940	.28520	3	2	66	2.05
117	2.5	D1	8.25	55.25	.11780	.37690	3	3	72	3.20
118	2.5	D1	6.00	49.25	.06520	.22270	4	1	84	3.42
119	2.5	D1	7.00	34.00	.09540	.21450	4	2	78	2.25
120	2.5	D1	8.25	48.50	.10030	.30640	4	3	74	3.05
121	2.5	D2	7.50	33.50	.08560	.26150	1	1	88	3.05
122	2.5	D2	8.50	35.75	.13080	.20710	1	2	77	1.58
123	2.5	D2	5.00	40.00	.17170	.27630	1	3	90	1.61
124	2.5	D2	12.00	39.75	.19860	.27220	2	1	68	1.37

	pH	drought	root area	shoot area	root wt	shoot wt	repl	samples	Ht	shoot/root wt. ratio
125	2.5	D2	7.50	36.25	.12550	.22460	2	2	64	1.79
126	2.5	D2	1.25	9.50	.02040	.04770	2	3	33	2.34
127	2.5	D2	5.25	29.75	.07360	.21710	3	1	70	2.95
128	2.5	D2	6.50	37.50	.08810	.23630	3	2	71	2.68
129	2.5	D2	7.75	31.75	.08950	.19190	3	3	68	2.14
130	2.5	D2	7.25	38.50	.12590	.25130	4	1	86	2.00
131	2.5	D2	7.25	5.25	.09450	.19090	4	2	75	2.02
132	2.5	D2	5.50	26.50	.11550	.18590	4	3	74	1.61
133	2.5	D3	6.00	10.00	.12420	.20810	1	1	90	1.68
134	2.5	D3	6.00	34.50	.11270	.25530	1	2	79	2.27
135	2.5	D3	6.25	55.50	.08590	.37870	1	3	86	4.41
136	2.5	D3	6.00	29.00	.09390	.17790	2	1	60	1.89
137	2.5	D3	6.25	20.50	.07780	.10690	2	2	44	1.37
138	2.5	D3	2.00	33.25	.03940	.23490	2	3	61	5.96
139	2.5	D3	9.00	44.75	.16990	.30460	3	1	75	1.79
140	2.5	D3	5.25	26.25	.05100	.16550	3	2	63	3.25
141	2.5	D3	5.00	56.25	.08140	.34680	3	3	71	4.26
142	2.5	D3	9.75	31.25	.15490	.20350	4	1	74	1.31
143	2.5	D3	4.50	34.25	.04100	.18110	4	2	73	4.42
144	2.5	D3	7.50	39.50	.09760	.27620	4	3	76	2.83

Appendix 5: Sand Experiment--Results

PART a. ELEMENT CONCENTRATIONS IN ROOTS (UNLABELLED ELEMENTS) AND SHOOTS

PART b. GROWTH DATA

LEGEND

D1 = CONTROL DROUGHT

D2 = INTERMEDIATE DROUGHT

D3 = SEVERE DROUGHT

ALL CONCENTRATIONS IN µg/g

a.

	pH	drought	trt Al	Al cat	rep	N	P	K	Ca	Mg	Cl	Na	Al	Mn	Shoot-N	Shoot-P	Shoot-K	Shoot-Ca	Shoot-Mg	Shoot-Mn	Shoot-Al	Shoot-Cl	Shoot-Na
1	5.5	D1	0	a=0	1	17424	1488.0	7508.1	1014.6	1420.5	2274	2130	715	19.9	15050	937.5	8250.0	10062.5	2250.0	30.2	57.3	3563.0	1280
2	5.5	D1	0	a=0	2	11267	941.8	11130.0	1327.1	1755.1	6242	2652	500	25.9	16975	1300.0	6812.5	15625.0	3437.5	64.7	61.6	4231.0	799
3	5.5	D1	0	a=0	3	6786	1233.8	16010.6	4847.2	4333.0	10052	2273	448	15.2	14350	950.0	8937.5	14937.5	2875.0	39.6	66.4	5391.0	393
4	5.5	D1	0	a=0	4	10500	912.5	11437.5	6062.5	3937.5	7811	1979	282	12.5	15050	925.0	7812.5	15062.5	3562.5	47.1	66.8	4940.0	250
5	5.5	D1	20	b=20	1	13583	1221.0	13219.6	1617.1	1738.4	9346	5385	923	14.9	20650	1562.5	11062.5	13562.5	3250.0	39.4	73.3	3326.0	902
6	5.5	D1	20	b=20	2	17308	1396.5	12591.6	1373.6	2003.2	6247	3944	755	•	17150	1037.5	7875.0	11937.5	2875.0	39.9	81.0	4402.0	1059
7	5.5	D1	20	b=20	3	13045	1255.5	10581.2	4422.0	2447.9	9583	2810	573	24.8	20650	1262.5	8437.5	14937.5	3187.5	41.2	125.3	4927.0	709
8	5.5	D1	20	b=20	4	11550	1037.5	10375.0	5937.5	3875.0	8313	2556	341	16.8	17675	1075.0	9437.5	16500.0	4062.5	64.6	101.3	7641.0	778
9	5.5	D1	100	c=100	1	16043	1321.3	10372.0	4846.0	2658.0	7605	4479	1707	45.1	18025	1212.5	7437.5	10250.0	2375.0	64.7	100.7	3239.0	1205
10	5.5	D1	100	c=100	2	12702	746.7	10189.8	1675.0	1744.8	6769	3555	1011	28.7	15750	1037.5	7125.0	16875.0	3562.5	65.7	160.4	6725.0	1495
11	5.5	D1	100	c=100	3	6200	1236.8	12367.8	4154.1	2407.5	9530	3836	1110	20.6	16358	1117.0	9062.0	12375.0	2687.0	43.7	247.0	5154.0	995
12	5.5	D1	100	c=100	4	11025	1037.5	8562.5	13625.0	4187.5	5182	2724	439	13.4	15225	1150.0	6250.0	16875.0	3312.5	44.4	90.9	4185.0	1062
13	5.5	D1	250	d=250	1	22167	1770.8	8020.8	312.5	1041.7	4741	5632	5034	32.5	19250	1337.5	7062.5	7437.5	1625.0	95.5	12.5	1012.0	3848
14	5.5	D1	250	d=250	2	14875	1137.5	9500.0	5687.5	3187.5	6796	4849	1136	31.6	14000	1050.0	5250.0	13437.5	3187.5	42.1	129.5	4775.0	2692
15	5.5	D1	250	d=250	3	16940	1551.5	10245.9	4244.7	2244.3	6859	5401	2627	58.8	21700	1262.5	8750.0	12312.5	2750.0	90.0	252.3	4792.0	2298
16	5.5	D1	250	d=250	4	16583	1267.6	7533.2	4000.4	2857.4	7804	4154	496	29.6	19950	1625.0	7125.0	15437.0	3625.0	96.9	151.2	1567.0	2707
17	5.5	D2	0	a=0	1	19392	1875.0	17567.6	591.2	1858.1	6930	3790	862	31.8	15400	1375.0	9187.5	9000.0	2000.0	39.4	55.7	2442.0	1201
18	5.5	D2	0	a=0	2	12355	1290.8	13896.2	5598.0	4215.0	7737	2346	620	37.6	16275	1050.0	7437.5	15187.5	3125.0	64.8	70.2	4834.0	916
19	5.5	D2	0	a=0	3	6650	1437.5	12875.0	4750.0	3500.0	7617	2921	721	21.2	15050	975.0	7312.5	13875.0	3000.0	64.7	93.7	1954.0	215
20	5.5	D2	0	a=0	4	16598	1572.2	11920.0	2835.0	2835.0	6229	1911	788	33.0	18440	1330.0	10875.0	15687.5	3125.0	58.6	64.2	7488.0	1352
21	5.5	D2	20	b=20	1	13389	1040.3	15184.6	1216.4	1761.8	6243	3176	1032	21.7	13650	900.0	8187.5	12750.0	2562.5	52.5	111.7	3182.0	1125
22	5.5	D2	20	b=20	2	13381	1161.8	11783.1	1524.4	1606.8	4099	3614	1179	29.3	16975	1200.0	6562.5	13562.5	2500.0	44.3	79.2	2494.0	1153
23	5.5	D2	20	b=20	3	12417	1538.2	10740.0	5820.4	4296.0	6666	1746	610	34.8	22504	1385.0	9687.5	15625.0	3062.0	98.7	157.6	1759.0	505
24	5.5	D2	20	b=20	4	14210	1204.0	10808.2	1409.8	2114.7	9260	3924	939	41.2	18375	1243.0	13499.0	7204.0	2661.0	121.2	172.3	7893.0	3387
25	5.5	D2	100	c=100	1	16406	1206.3	9306.0	3102.0	1780.8	7535	5200	827	27.8	19775	1275.0	8187.5	12312.5	2937.5	61.2	178.0	3381.0	1432
26	5.5	D2	100	c=100	2	11550	1087.5	9625.0	4750.0	3000.0	5168	3578	703	22.2	13650	825.0	6625.0	13437.5	2875.0	36.4	67.4	5562.0	1397
27	5.5	D2	100	c=100	3	11725	1087.5	10000.0	5812.5	3500.0	7417	2561	354	12.5	19775	1125.0	9687.5	10625.0	2687.5	32.4	153.0	5272.0	1215
28	5.5	D2	100	c=100	4	13794	1302.6	10562.8	2797.3	2546.8	6146	2669	948	26.9	18200	1487.5	8312.5	15875.0	3687.5	81.3	115.8	7508.0	1434
29	5.5	D2	250	d=250	1	21903	1851.8	12053.0	1117.5	1516.6	11088	8619	2110	•	22050	1562.5	8437.5	11437.5	2625.0	65.1	128.1	6132.0	2750
30	5.5	D2	250	d=250	2	14645	1549.2	13109.1	4833.2	3111.8	9504	5045	512	•	21350	1225.0	9375.0	12187.5	2250.0	58.5	83.1	5891.0	2106
31	5.5	D2	250	d=250	3	11400	1071.4	11500.0	3857.0	2928.6	9670	5441	1612	35.9	15225	950.0	7937.5	13000.0	2875.0	76.9	268.3	2532.0	969
32	5.5	D2	250	d=250	4	9800	1000.0	5687.5	5812.5	3375.0	6226	5584	528	22.0	17500	1437.5	8750.0	19250.0	3687.0	44.2	145.1	10356.0	1918
33	5.5	D3	0	a=0	1	17213	1551.5	14490.6	1171.0	1756.4	8070	3690	1079	19.7	23100	1500.0	8062.5	11312.5	2437.5	51.0	79.6	4593.0	591
34	5.5	D3	0	a=0	2	16784	1422.6	13547.0	1998.1	2277.8	7678	2997	346	30.0	19075	1525.0	10187.5	16125.0	3187.0	92.0	60.2	8728.0	1254
35	5.5	D3	0	a=0	3	12250	1425.0	8375.0	5375.0	4125.0	7275	2061	292	20.9	18025	1037.5	10437.5	17125.0	3437.5	83.3	135.3	9733.0	688
36	5.5	D3	0	a=0	4	11200	1162.5	8625.0	5750.0	4187.5	6005	2279	431	18.9	18550	1062.5	9187.5	20750.0	3687.5	52.1	98.1	8746.0	727
37	5.5	D3	20	b=20	1	19637	1464.5	18358.0	5569.0	3197.0	6456	4478	1106	34.2	22400	1575.0	8437.5	12812.5	2875.0	55.0	88.1	4908.0	1148
38	5.5	D3	20	b=20	2	10500	762.5	7000.0	5125.0	2125.0	4004	3263	723	•	15575	825.0	5750.0	17437.5	3812.5	28.0	73.6	3144.0	722
39	5.5	D3	20	b=20	3	15000	1721.9	13456.6	4209.2	2551.0	8748	2305	1243	17.5	25725	1387.5	9500.0	11812.5	3000.0	31.5	250.4	5829.0	1724
40	5.5	D3	20	b=20	4	17754	1513.9	8863.9	3170.3	2911.5	6333	2707	532	36.0	31336	1225.0	9792.0	8574.0	2346.0	67.2	103.4	9144.0	1716
41	5.5	D3	100	c=100	1	13556	1153.0	3433.1	1628.5	660.2	8684	5017	1118	22.1	17850	1162.5	8062.5	10312.5	2250.0	27.1	55.8	3955.0	1350
42	5.5	D3	100	c=100	2	16802	1301.7	11170.6	2954.2	1938.7	7174	4848	857	66.4	17850	1300.0	9562.5	12187.5	2750.0	50.6	74.4	5133.0	1313
43	5.5	D3	100	c=100	3	15572	1257.9	12579.4	7282.8	4104.9	7566	3457	716	11.0	21175	1362.5	8812.5	13000.0	3375.0	29.4	183.7	6221.0	814
44	5.5	D3	100	c=100	4	13215	1277.0	4372.5	22209.0	3262.0	3447	2964	538	16.1	17675	1575.0	5125.0	15437.0	3875.0	59.6	201.0	6373.0	1204
45	5.5	D3	250	d=250	1	24027	3060.5	6006.9	429.1	1287.2	6213	9751	6322	33.4	27326	1778.0	7486.5	9625.7	2740.6	50.8	260.4	8788.0	5853
46	5.5	D3	250	d=250	2	14532	976.4	9632.3	3034.8	1539.4	7320	4443	660	•	14175	925.0	5375.0	12875.0	3375.0	53.2	154.9	5113.0	2352
47	5.5	D3	250	d=250	3	12250	1100.0	11562.5	4437.5	3625.0	8791	6121	1060	35.2	17675	1012.5	7812.5	14562.5	3312.5	62.9	261.7	4448.0	1237
48	5.5	D3	250	d=250	4	20172	2981.3	11135.0	2694.0	2694.0	7796	6101	3785	57.2	39465	1049.0	11162.0	5452.7	2109.0	57.9	690.4	8369.0	5967
49	4.5	D1	0	a=0	1	19387	1656.8	13291.3	4018.3	2905.5	8037	2507	1006	25.9	30975	1825.0	10812.5	11562.5	3125.0	85.9	93.7	7211.0	678
50	4.5	D1	0	a=0	2	13300	1712.5	10250.0	5750.0	3250.0	4593	1403	476	36.2	18550	1650.0	8375.0	16125.0	3687.0	74.8	60.5	5475.0	913
51	4.5	D1	0	a=0	3	13403	1050.0	15364.4	7103.1	3628.8	9890	3077	632	24.9	19425	1225.0	8687.5	13500.0	2812.5	63.0	112.8	3418.0	527
52	4.5	D1	0	a=0	4	20860	1986.7	11106.5	2621.4	2345.5	5739	1862	581	17.3	27650	1937.5	7687.5	13000.0	2500.0	85.8	100.5	9841.0	1799
53	4.5	D1	20	b=20	1	18889	1746.0	13889.0	10119.0	5158.7	6420	2190	789	•	22225	1275.0	10250.0	8375.0	1750.0	53.0	61.5	2177.0	1023
54	4.5	D1	20	b=20	2	13941	1795.0	12383.0	5175.6	3865.3	5282	1577	709	37.0	15225	1125.0	8187.5	15875.0	3437.0	43.1	60.1	4296.0	821
55	4.5	D1	20	b=20	3	17469	1392.6	7742.9	3453.6	2061.0	7057	1962	1420	21.1	29104	1891.0	8516.0	12607.0	3420.0	93.8	212.8	11417.0	1679
56	4.5	D1	20	b=20	4	18200	1212.5	9625.0	1112.5	3562.5	6117	2405	365	15.2	18375	1250.0	7250.0	17375.0	3812.0	50.0	73.7	5884.0	583
57	4.5	D1	100	c=100	1	16330	1560.5	6551.0	2679.7	1891.5	8296	4588	1991	24.2	17675	1200.0	68125.7	9000.0	2062.5	46.1	66.7	3041.0	2740
58	4.5	D1	100	c=100	2	11331	884.0	9292.6	2210.7	1836.0	3413	2956	1049	39.6	9450	812.5	7000.0	15437.5	2750.0	77.5	140.5	3870.0	1274
59	4.5	D1	100	c=100	3	13315	1317.9	9239.0	5163.0	2853.3	6819	3155	369	16.8	21000	1262.5	8875.0	15437.5	2625.0	39.3	191.6	6092.0	1430
60	4.5	D1	100	c=100	4	10675	1112.5	7375.0	5687.5	3937.5	6658	3012	523	30.4	17850	1287.5	7937.0	16937.0	3375.0	40.4	123.9	7167.0	1316
61	4.5	D1	250	d=250	1	18154	1628.5	11761.0	3241.9	2111.0	10744	7559	1887	•	19775	1425.0	8000.0	9937.5	2375.0	66.2	128.8	4717.0	2448
62	4.5	D1	250	d=250	2	13300	1975.0	9500.0	5187.5	3812.5	6505	2279	1008	48.8	16450	1637.5	8500.0	14750.0	3187.5	70.4	102.8	3097.0	1078

	pH	drought	trt Al	Al cat	rep	N	P	K	Ca	Mg	Cl	Na	Al	Mn	Shoot-N	Shoot-P	Shoot-K	Shoot-Ca	Shoot-Mg	Shoot-Mn	Shoot-Al	Shoot-Cl	Shoot-Na
63	4.5	D1	250	d=250	3	10850	862.5	6750.0	4875.0	3000.0	6693	5273	718	19.3	14700	912.5	7750.0	15000.0	3187.5	46.3	222.9	5147.0	933
64	4.5	D1	250	d=250	4	13850	1526.0	9398.0	5370.3	3674.4	6927	4169	778	33.1	18725	1675.0	8187.0	15687.0	3437.0	66.7	123.9	8188.0	1801
65	4.5	D2	0	a=0	1	17322	1475.2	12690.0	2538.0	1983.0	4452	3450	464	25.1	16450	1087.5	8312.5	9250.0	2437.5	33.4	37.5	2610.0	632
66	4.5	D2	0	a=0	2	10675	1325.0	11687.5	6187.5	3625.0	7321	1826	669	32.5	15925	1237.5	8437.5	17062.5	3812.5	56.3	56.1	4793.0	418
67	4.5	D2	0	a=0	3	11200	1050.0	9125.0	5187.5	3250.0	5915	1658	540	28.8	16975	1200.0	8812.5	15687.5	3500.0	89.3	179.8	8568.0	356
68	4.5	D2	0	a=0	4	12645	1039.5	8776.4	3067.5	2598.8	6721	2224	262	21.1	19075	1325.0	11375.0	18937.5	3937.5	66.0	97.0	10260.0	1096
69	4.5	D2	20	b=20	1	14676	1305.3	10680.4	3164.6	1977.8	8630	2262	919	21.9	21000	1300.0	10375.0	11125.0	2625.0	67.7	65.1	7545.0	990
70	4.5	D2	20	b=20	2	11200	1487.5	11000.0	4812.5	3562.5	6251	1832	543	21.9	15750	1325.0	7625.0	18187.5	3500.0	40.7	61.6	3266.0	489
71	4.5	D2	20	b=20	3	13125	1275.0	10687.5	4687.5	3000.0	5901	1749	409	28.5	18550	1287.5	9750.0	16937.5	3312.5	72.6	158.8	7499.0	280
72	4.5	D2	20	b=20	4	15312	1203.1	9921.9	3281.3	2187.5	6468	2487	887	46.4	16044	1393.0	11415.0	7669.0	2689.0	96.4	103.6	5594.0	1035
73	4.5	D2	100	c=100	1	17439	1365.8	12019.0	2786.3	1803.0	6933	4659	1894	27.6	18550	1237.5	7875.0	10875.0	2750.0	52.7	120.9	2807.0	1106
74	4.5	D2	100	c=100	2	11900	1025.0	10562.5	5625.0	3500.0	5206	4609	1178	41.6	13825	800.0	6375.0	15562.5	3250.0	43.5	62.8	2915.0	976
75	4.5	D2	100	c=100	3	16540	1559.5	10219.7	3603.5	2481.0	6391	1914	500	20.9	21525	1650.0	12062.5	15562.5	2875.0	113.7	163.0	14015.0	1949
76	4.5	D2	100	c=100	4	8750	637.5	7062.5	4750.0	3812.5	8314	1836	362	21.7	15575	1325.0	6437.5	14937.0	4062.0	29.4	137.5	6918.0	2055
77	4.5	D2	250	d=250	1	16693	1374.3	11823.0	2375.0	1566.0	8863	6532	2818	31.6	18375	1212.5	8062.5	9000.0	1937.5	68.0	142.9	4391.0	1827
78	4.5	D2	250	d=250	2	11900	1337.5	9250.0	4687.5	3437.5	5723	2879	1616	46.9	16100	1012.5	7062.5	6250.0	3875.0	58.8	109.4	4233.0	1208
79	4.5	D2	250	d=250	3	14439	1264.5	8728.7	3469.1	2350.0	7527	9653	1536	25.8	19775	1412.5	9562.5	10687.5	2875.0	60.9	304.3	4264.0	1863
80	4.5	D2	250	d=250	4	10748	879.4	7328.3	2442.8	2093.8	5582	1715	4150	41.8	18956	1550.0	8188.0	15253.0	3829.0	121.7	485.0	9985.0	742
81	4.5	D3	0	a=0	1	15256	1720.4	11868.0	2831.0	1959.9	8947	3741	1596	.	25550	1887.5	9625.0	10062.5	2625.0	28.1	79.8	2555.0	570
82	4.5	D3	0	a=0	2	9975	1762.5	10312.5	5687.5	3437.5	6888	3146	259	20.4	19425	1525.0	8500.0	18562.0	4187.0	51.1	110.8	9480.0	2035
83	4.5	D3	0	a=0	3	15265	1169.7	9862.2	4014.7	2973.8	7517	2864	712	20.5	19573	1334.0	7250.0	13250.0	2750.0	52.1	151.9	7897.0	1746
84	4.5	D3	0	a=0	4	13305	1491.5	10493.7	2837.9	2969.9	8056	2243	348	25.2	16625	1350.0	9812.5	15437.5	3750.0	56.7	70.3	8976.0	811
85	4.5	D3	20	b=20	1	17304	1375.6	13307.4	2940.6	2093.3	9672	2835	680	.	21875	1287.5	9875.0	11125.0	3062.5	57.9	98.2	5535.0	636
86	4.5	D3	20	b=20	2	11797	1217.2	11169.0	4815.4	3277.1	4914	1789	666	33.4	16275	1087.5	7250.0	17625.0	3687.0	55.2	114.4	4568.0	779
87	4.5	D3	20	b=20	3	11755	839.7	9669.2	8206.1	4325.7	7127	1832	512	24.2	17500	1112.5	9937.5	15625.0	2875.0	63.2	187.4	9267.0	681
88	4.5	D3	20	b=20	4	11218	901.4	8814.1	3756.0	3004.8	7600	1961	335	14.0	17467	1092.0	5562.5	24562.5	2187.5	34.6	116.1	3800.0	1393
89	4.5	D3	100	c=100	1	14634	1669.6	11759.0	3048.8	2105.0	6375	4478	2305	45.8	19425	1362.5	8750.0	10562.5	2500.0	45.4	101.0	3408.0	1286
90	4.5	D3	100	c=100	2	11725	962.5	10250.0	5875.0	3187.5	6560	.	448	35.6	14000	837.5	6750.0	15125.0	2875.0	42.4	84.2	3379.0	982
91	4.5	D3	100	c=100	3	13735	1121.0	12359.8	8154.9	3504.0	9222	4961	799	28.9	21175	1312.5	9500.0	15062.5	2875.0	44.2	163.3	2716.0	536
92	4.5	D3	100	c=100	4	9450	562.5	7562.5	4687.5	3375.0	6437	2842	456	23.7	14875	750.0	7750.0	16637.0	4875.0	75.4	220.9	9105.0	647
93	4.5	D3	250	d=250	1	16289	1930.9	10840.0	3048.8	1693.8	8448	5908	3202	69.2	23450	1600.0	6875.0	9062.5	2500.0	46.8	168.0	5752.0	2567
94	4.5	D3	250	d=250	2	15033	1390.4	10049.6	5713.1	3097.5	6233	2968	976	39.7	16100	1325.0	8937.0	16000.0	3125.0	37.1	131.6	6629.0	1547
95	4.5	D3	250	d=250	3	14258	946.8	10303.9	2068.7	1989.2	8631	6546	968	28.5	16975	1075.0	7312.5	11500.0	2625.0	43.6	261.3	2149.0	1387
96	4.5	D3	250	d=250	4	16625	1662.8	9604.3	2580.3	1863.5	7198	5465	1891	42.4	29914	1925.0	8062.5	8250.0	2375.0	51.2	227.7	6534.0	2759
97	3.5	D1	0	a=0	1	17318	1567.9	12298.6	2805.0	1942.0	3783	2453	430	20.9	16975	1187.5	9375.0	7937.5	2187.5	40.4	41.8	2524.0	742
98	3.5	D1	0	a=0	2	11864	1040.0	13803.3	7190.5	3787.9	8278	2350	456	22.2	16100	1250.0	7500.0	16872.0	3500.0	52.9	56.5	3668.0	378
99	3.5	D1	0	a=0	3	16538	1482.6	13319.7	2049.2	2832.7	7455	1723	581	24.1	23625	1606.0	10887.0	15242.0	2722.0	89.3	135.0	10044.0	783
100	3.5	D1	0	a=0	4	15845	1470.7	13601.6	2023.4	2248.2	7897	2771	1157	53.5	26479	1431.0	12035.0	7006.0	2106.0	69.4	104.1	7938.0	2296
101	3.5	D1	20	b=20	1	16421	1333.9	15122.0	2702.0	2415.0	7985	3068	782	25.4	15750	1025.0	7750.0	10750.0	2500.0	75.4	58.3	1917.0	383
102	3.5	D1	20	b=20	2	10325	900.0	13062.5	7187.5	3750.0	6546	1347	286	24.9	12600	1125.0	7812.5	15875.0	2750.0	69.2	28.9	3184.0	419
103	3.5	D1	20	b=20	3	12461	1715.7	12448.4	5482.5	3805.5	7273	2218	613	30.9	19425	1112.5	10625.0	15343.0	3187.5	77.9	217.0	8133.0	694
104	3.5	D1	20	b=20	4	13043	1388.9	10438.2	2415.4	2113.5	7921	1773	720	29.4	20319	1662.5	7779.8	14840.0	3334.0	95.9	171.5	8613.0	471
105	3.5	D1	100	c=100	1	14693	1112.9	12073.0	1739.0	1391.0	6507	1114	3011	40.8	20875	1187.5	7937.5	10812.0	3000.0	145.3	334.2	4168.0	679
106	3.5	D1	100	c=100	2	13125	1546.0	11842.0	4111.8	2878.3	4192	1153	1962	33.8	15400	1300.0	6312.5	13562.5	3250.0	105.5	184.4	5924.0	506
107	3.5	D1	100	c=100	3	11142	1154.8	10104.5	2887.0	1911.7	6790	1739	2010	53.3	17675	1037.5	10750.0	22125.0	3562.5	118.9	424.6	9694.0	346
108	3.5	D1	100	c=100	4	9800	987.5	7375.0	2937.5	2437.5	5262	1692	1572	43.8	16450	1425.0	7000.0	15937.5	3750.0	76.8	335.3	4975.0	452
109	3.5	D1	250	d=250	1	14161	1856.6	12408.0	1195.0	1011.0	3867	1570	5429	38.2	21875	1225.0	8750.0	6375.0	2062.5	67.3	416.3	2886.0	885
110	3.5	D1	250	d=250	2	11025	1300.0	6187.5	3312.5	1937.5	3614	1308	3476	25.5	13475	812.5	6500.0	14125.0	3312.5	44.2	209.2	2856.0	831
111	3.5	D1	250	d=250	3	11560	1253.8	8677.4	4357.8	1681.9	7354	2450	3703	51.4	15925	937.5	8875.0	17500.0	3187.5	74.7	542.3	7103.0	988
112	3.5	D1	250	d=250	4	14000	2008.0	8401.6	614.7	1024.6	4975	2659	6009	44.1	33410	981.0	9168.0	3784.0	1601.0	103.7	664.2	4213.0	2031
113	3.5	D2	0	a=0	1	17683	1342.0	13101.0	2620.0	2364.5	10369	1833	500	29.2	24850	1512.5	9437.5	12750.0	2750.0	92.2	65.3	6972.0	815
114	3.5	D2	0	a=0	2	14079	1539.9	12806.4	8720.9	4321.0	7441	2306	336	29.5	13825	1037.5	7000.0	14937.5	3437.5	50.0	59.6	5460.0	684
115	3.5	D2	0	a=0	3	16604	1661.0	11528.0	2128.3	2439.8	8249	2408	397	17.7	23207	1562.5	8356.0	12636.0	2581.5	28.3	122.3	5311.0	790
116	3.5	D2	0	a=0	4	14861	1292.0	10384.6	6307.7	4384.6	5953	1469	327	21.8	23292	1250.0	8687.5	19750.0	3625.0	57.0	72.0	5866.0	764
117	3.5	D2	20	b=20	1	12166	2055.9	14083.0	2673.0	2261.5	5891	2396	1357	40.5	21350	1375.0	9250.0	9750.0	2437.5	72.2	82.3	3969.0	1333
118	3.5	D2	20	b=20	2	9975	1150.0	11062.5	6250.0	3750.0	6512	1872	647	40.2	13475	975.0	6375.0	17187.5	3562.5	89.5	58.6	4715.0	610
119	3.5	D2	20	b=20	3	14593	1416.9	10219.9	3990.2	2443.0	7222	1579	516	28.9	22225	1387.5	9562.5	23500.0	3750.0	123.2	187.4	10663.0	897
120	3.5	D2	20	b=20	4	14450	2214.2	19285.0	4642.8	3928.0	7262	1953	792	44.5	23100	1668.0	8736.0	5376.0	2138.0	126.1	192.0	7856.0	1510
121	3.5	D2	100	c=100	1	12400	1397.8	13628.0	1647.4	1348.0	7038	2241	3085	35.3	24500	1550.0	8687.5	11375.0	3062.5	129.4	283.6	5799.0	353
122	3.5	D2	100	c=100	2	15249	1037.0	13550.0	4797.7	3501.0	8078	1981	2234	46.0	17675	900.0	9817.5	18812.0	3750.0	86.4	158.2	7077.0	390
123	3.5	D2	100	c=100	3	15354	1589.0	11694.3	2741.7	2350.0	8224	1292	2161	52.5	21700	1475.0	10562.0	18812.0	3750.0	144.3	315.9	10459.0	1362
124	3.5	D2	100	c=100	4	9134	1232.0	9590.0	3262.0	2740.0	5679	1870	3182	34.3	17325	1287.0	6125.0	18812.0	3750.0	71.2	164.8	4692.0	638

	pH	drought	trt Al	Al cat	rep	N	P	K	Ca	Mg	Cl	Na	Al	Mn	Shoot-N	Shoot-P	Shoot-K	Shoot-Ca	Shoot-Mg	Shoot-Mn	Shoot-Al	Shoot-Cl	Shoot-Na
125	3.5	D2	250	d=250	1	16906	1745.7	10375.5	1399.9	1070.5	5754	1600	5244	37.4	25760	1640.0	8866.7	10266.7	2866.7	94.9	490.3	8564.0	687
126	3.5	D2	250	d=250	2	10850	1050.0	8750.0	4250.0	1750.0	3382	1544	2447	30.9	14000	812.5	5687.5	13062.5	3187.5	58.2	192.2	3538.0	240
127	3.5	D2	250	d=250	3	12035	1228.0	9473.7	1886.0	1315.8	4515	1622	4118	31.7	14525	1062.5	8500.0	15062.0	3125.0	58.9	537.7	4462.0	471
128	3.5	D2	250	d=250	4	9275	725.0	6062.5	5750.0	3375.0	4870	2619	756	35.5	15575	1125.0	6562.5	16750.0	3437.5	67.2	249.7	2509.0	1202
129	3.5	D3	0	a=0	1	12236	1573.2	13936.4	2479.5	2052.0	8413	2764	335	40.4	17675	1087.5	8437.5	8687.5	2125.0	58.1	33.9	3436.0	535
130	3.5	D3	0	a=0	2	9975	737.5	13750.0	7187.5	4562.5	8405	2116	304	24.5	14000	775.0	7687.5	22312.0	3937.5	39.1	49.8	2807.0	266
131	3.5	D3	0	a=0	3	12197	1683.0	16961.7	2212.4	2857.7	9357	2881	692	42.4	25310	975.0	11000.0	11687.0	4565.0	34.0	157.0	7030.0	1235
132	3.5	D3	0	a=0	4	8050	812.5	8250.0	6562.5	3687.5	6100	1236	431	18.8	16275	825.0	8812.5	21812.0	4000.0	78.6	122.8	6087.0	141
133	3.5	D3	20	b=20	1	15427	1220.8	11733.0	2700.9	1728.6	4914	2530	639	36.9	15225	987.5	8687.5	9812.5	2250.0	52.5	47.6	2333.0	402
134	3.5	D3	20	b=20	2	14947	1084.0	12565.7	7391.6	3613.7	6469	2064	872	57.4	16975	1387.5	7062.5	12125.0	2875.0	60.0	41.1	5144.0	809
135	3.5	D3	20	b=20	3	13077	1401.0	13392.9	4670.3	3914.8	6943	1529	744	43.3	17675	975.0	9812.5	16875.0	3625.0	68.5	144.4	3551.0	318
136	3.5	D3	20	b=20	4	13450	1037.0	9770.7	3438.9	2893.0	8602	2157	567	23.5	22657	1637.5	10404.0	13409.0	4161.5	54.3	116.3	11485.0	1146
137	3.5	D3	100	c=100	1	14339	981.0	12982.0	5193.0	2524.5	6478	1994	2658	37.3	17150	962.5	8875.0	11125.0	2812.5	105.4	147.4	5803.0	516
138	3.5	D3	100	c=100	2	12425	950.0	12375.0	4375.0	2687.5	7087	1641	2361	49.1	16100	825.0	8437.5	18750.0	4125.0	91.5	176.6	4252.0	.
139	3.5	D3	100	c=100	3	14327	904.6	10188.2	1964.5	1964.5	7539	1616	2709	32.6	19534	1537.5	8448.5	16833.0	3968.0	96.8	366.2	8348.0	507
140	3.5	D3	100	c=100	4	16878	1428.0	11817.9	2141.5	3093.3	7285	1287	3480	59.3	26250	1912.5	10745.0	12464.0	2937.0	71.8	262.1	5633.0	897
141	3.5	D3	250	d=250	1	16908	1380.0	10395.0	1768.5	1682.2	6325	1532	3766	44.6	22050	1462.5	8187.5	12187.5	2875.0	96.3	391.2	3048.0	505
142	3.5	D3	250	d=250	2	12600	800.0	9000.0	3000.0	1875.0	4155	1326	3383	33.0	14700	1037.5	7562.5	15000.0	3875.0	59.5	135.2	5505.0	272
143	3.5	D3	250	d=250	3	17632	1280.0	11492.4	1941.6	1679.3	6850	1781	3832	45.5	19775	2037.5	8937.5	13312.5	3062.5	113.9	542.2	5844.0	.
144	3.5	D3	250	d=250	4	10850	1162.5	7562.5	3187.5	2312.5	6425	1544	3529	36.7	17675	1475.0	6062.5	14750.0	3812.5	68.9	561.2	7054.0	688

	pH	drought	root area	shoot area	root wt	shoot wt	repl	samples	Ht	shoot/root wt. ratio
1	5.5	control	2.00	14.50	.02659	.08109	1	1	52	3.05
2	5.5	control	1.00	19.50	.01368	.07957	1	2	42	5.82
3	5.5	control	4.25	26.25	.05894	.18749	1	3	60	3.18
4	5.5	control	1.00	2.50	.01029	.02006	2	1	43	1.95
5	5.5	control	5.25	10.50	.06159	.07236	2	2	43	1.17
6	5.5	control	5.05	22.00	.08311	.13678	2	3	55	1.65
7	5.5	control	2.75	21.00	.05649	.12637	3	1	65	2.24
8	5.5	control	3.50	12.00	.05224	.06747	3	2	43	1.29
9	5.5	control	8.75	16.50	.07186	.09390	3	3	55	1.31
10	5.5	control	3.00	12.00	.04907	.06721	4	1	55	1.37
11	5.5	control	6.25	14.00	.09164	.10192	4	2	44	1.11
12	5.5	control	9.00	22.50	.17017	.16135	4	3	58	.95
13	5.5	control	4.00	24.25	.03991	.10745	1	1	32	2.69
14	5.5	control	3.00	15.50	.04604	.08671	1	2	47	1.88
15	5.5	control	6.00	20.75	.07824	.13941	1	3	55	1.78
16	5.5	control	1.50	17.00	.03049	.09170	2	1	60	3.01
17	5.5	control	5.25	17.25	.06494	.11206	2	2	58	1.73
18	5.5	control	1.75	10.75	.02125	.09762	2	3	42	4.59
19	5.5	control	4.25	14.75	.03978	.11452	3	1	40	2.88
20	5.5	control	4.50	14.50	.04376	.07447	3	2	35	1.70
21	5.5	control	6.25	10.50	.08144	.06721	3	3	42	.83
22	5.5	control	5.00	12.75	.07309	.06911	4	1	46	.95
23	5.5	control	4.75	12.50	.16115	.17723	4	2	52	1.10
24	5.5	control	13.00	22.25	.04550	.07061	4	3	53	1.55
25	5.5	control	1.00	12.75	.02033	.11649	1	1	60	5.73
26	5.5	control	2.00	15.75	.02460	.06966	1	2	60	2.83
27	5.5	control	4.00	23.50	.06819	.15298	1	3	72	2.24
28	5.5	control	4.50	17.75	.05684	.10429	2	1	66	1.83
29	5.5	control	6.25	14.00	.05545	.11586	2	2	45	2.09
30	5.5	control	6.25	18.25	.07437	.13056	2	3	50	1.76
31	5.5	control	6.50	18.50	.08153	.11755	3	1	55	1.44
32	5.5	control	2.50	13.50	.03429	.08337	3	2	60	2.43
33	5.5	control	1.75	12.25	.02399	.08032	3	3	75	3.35
34	5.5	control	5.50	14.00	.06954	.08541	4	1	45	1.23
35	5.5	control	10.00	16.00	.12791	.14237	4	2	71	1.11
36	5.5	control	8.50	17.00	.10132	.14221	4	3	47	1.40
37	5.5	control	1.00	15.75	.01559	.09625	1	1	52	6.17
38	5.5	control	2.00	14.50	.02554	.08674	1	2	57	3.40
39	5.5	control	2.00	20.00	.02472	.11948	1	3	57	4.83
40	5.5	control	6.90	19.50	.08939	.12842	2	1	40	1.44
41	5.5	control	4.10	19.75	.07458	.13460	2	2	50	1.80
42	5.5	control	4.10	13.50	.06105	.08685	2	3	29	1.42
43	5.5	control	4.00	13.50	.04682	.08645	3	1	50	1.85
44	5.5	control	5.25	18.75	.04736	.12282	3	2	47	2.59
45	5.5	control	5.00	17.75	.04230	.11897	3	3	60	2.81
46	5.5	control	2.25	10.75	.04075	.05574	4	1	36	1.37
47	5.5	control	5.50	21.00	.07350	.03684	4	2	47	.50
48	5.5	control	1.50	6.50	.01946	.04806	4	3	32	2.47
49	5.5	intermediate	1.00	14.00	.02505	.09288	1	1	50	3.71
50	5.5	intermediate	1.25	15.50	.02930	.11127	1	2	60	3.80
51	5.5	intermediate	1.00	11.25	.02477	.06111	1	3	50	2.47
52	5.5	intermediate	7.00	15.00	.09158	.08979	2	1	48	.98
53	5.5	intermediate	4.00	14.00	.04452	.08985	2	2	39	2.02
54	5.5	intermediate	7.00	20.50	.06651	.12330	2	3	50	1.85
55	5.5	intermediate	6.00	16.00	.07651	.10116	3	1	55	1.32
56	5.5	intermediate	3.25	14.75	.05619	.09747	3	2	69	1.73
57	5.5	intermediate	6.00	21.25	.07693	.16309	3	3	73	2.12
58	5.5	intermediate	1.25	5.25	.02104	.04208	4	1	44	2.00
59	5.5	intermediate	.25	7.75	.02127	.07043	4	2	48	3.31
60	5.5	intermediate	5.50	13.00	.06512	.10131	4	3	50	1.56
61	5.5	intermediate	5.25	23.00	.08279	.15178	1	1	50	1.83
62	5.5	intermediate	4.00	25.00	.05225	.16922	1	2	55	3.24

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	pH	drought	root area	shoot area	root wt	shoot wt	repl	samples	Ht	shoot/root wt. ratio
63	5.5	intermediate	1.50	10.50	.02484	.07056	1	3	50	2.84
64	5.5	intermediate	3.25	24.50	.03822	.13729	2	1	56	3.59
65	5.5	intermediate	5.25	17.00	.03112	.10786	2	2	56	3.47
66	5.5	intermediate	8.00	22.00	.09032	.13149	2	3	61	1.46
67	5.5	intermediate	3.00	7.00	.02892	.04652	3	1	44	1.61
68	5.5	intermediate	5.00	9.00	.05205	.05915	3	2	41	1.14
69	5.5	intermediate	10.00	19.50	.11140	.10643	3	3	43	.96
70	5.5	intermediate	2.25	9.50	.01615	.06505	4	1	32	4.03
71	5.5	intermediate	1.00	3.75	.00363	.01311	4	2	13	3.61
72	5.5	intermediate	1.50	2.50	.00950	.02805	4	3	23	2.95
73	5.5	intermediate	8.25	25.25	.08853	.16931	1	1	50	1.91
74	5.5	intermediate	2.00	12.50	.01323	.07813	1	2	65	5.91
75	5.5	intermediate	1.00	17.75	.01621	.10156	1	3	70	6.27
76	5.5	intermediate	5.00	19.25	.09655	.10991	2	1	51	1.14
77	5.5	intermediate	3.50	30.25	.08304	.21961	2	2	57	2.64
78	5.5	intermediate	3.00	13.75	.03558	.08627	2	3	55	2.42
79	5.5	intermediate	2.00	10.50	.01370	.05691	3	1	57	4.15
80	5.5	intermediate	7.25	21.00	.07542	.13976	3	2	55	1.85
81	5.5	intermediate	7.50	15.75	.12548	.11645	3	3	57	.93
82	5.5	intermediate	2.25	20.00	.02793	.11443	4	1	50	4.10
83	5.5	intermediate	2.25	8.00	.03203	.04941	4	2	29	1.54
84	5.5	intermediate	8.00	16.00	.10022	.11545	4	3	42	1.15
85	5.5	intermediate	4.00	24.25	.03184	.12156	1	1	65	3.82
86	5.5	intermediate	3.00	22.75	.02629	.07903	1	2	62	3.01
87	5.5	intermediate	3.00	15.50	.02436	.08391	1	3	55	3.44
88	5.5	intermediate	1.90	24.70	.02154	.13193	2	1	72	6.12
89	5.5	intermediate	7.50	23.10	.12336	.15157	2	2	49	1.23
90	5.5	intermediate	3.80	14.30	.05251	.08913	2	3	41	1.70
91	5.5	intermediate	7.25	22.00	.11213	.16128	3	1	70	1.44
92	5.5	intermediate	5.00	20.00	.05636	.13159	3	2	45	2.33
93	5.5	intermediate	1.00	7.25	.01531	.05181	3	3	55	3.38
94	5.5	intermediate	9.25	14.25	.11971	.09458	4	1	42	.79
95	5.5	intermediate	6.00	16.00	.13016	.12944	4	2	50	.99
96	5.5	intermediate	6.00	17.00	.06874	.11420	4	3	45	1.66
97	5.5	severe	2.00	10.50	.02541	.05989	1	1	60	2.36
98	5.5	severe	5.00	19.00	.05641	.10977	1	2	60	1.95
99	5.5	severe	1.00	18.00	.00962	.11671	1	3	57	12.13
100	5.5	severe	7.00	21.50	.07689	.12061	2	1	39	1.57
101	5.5	severe	7.00	20.00	.05607	.12318	2	2	42	2.20
102	5.5	severe	3.50	11.00	.03005	.06447	2	3	47	2.15
103	5.5	severe	3.25	9.25	.04835	.07426	3	1	47	1.54
104	5.5	severe	5.75	18.25	.07983	.12354	3	2	70	1.55
105	5.5	severe	12.50	25.25	.01581	.16471	3	3	52	10.42
106	5.5	severe	8.25	13.00	.10960	.08445	4	1	34	.77
107	5.5	severe	7.00	12.00	.08783	.08048	4	2	51	.92
108	5.5	severe	5.25	14.00	.08131	.09058	4	3	42	1.11
109	5.5	severe	1.00	7.25	.01054	.06074	1	1	40	5.76
110	5.5	severe	2.00	24.25	.03119	.10753	1	2	60	3.45
111	5.5	severe	3.00	13.00	.02413	.09604	1	3	50	3.98
112	5.5	severe	7.25	24.00	.11735	.12354	2	1	46	1.05
113	5.5	severe	15.75	26.75	.13958	.13820	2	2	35	.99
114	5.5	severe	7.00	14.00	.07529	.09538	2	3	57	1.27
115	5.5	severe	4.75	16.75	.05337	.09931	3	1	57	1.86
116	5.5	severe	1.75	9.50	.01416	.05418	3	2	45	3.83
117	5.5	severe	4.50	12.00	.03760	.06424	3	3	35	1.71
118	5.5	severe	5.50	12.75	.08004	.09166	4	1	53	1.15
119	5.5	severe	1.00	2.75	.01296	.03534	4	2	8	2.73
120	5.5	severe	1.25	5.00	.01242	.03328	4	3	40	2.68
121	5.5	severe	2.00	13.50	.02774	.06738	1	1	42	2.43
122	5.5	severe	3.00	23.25	.04005	.12569	1	2	70	3.14
123	5.5	severe	2.25	21.00	.08332	.12581	1	3	57	1.51
124	5.5	severe	3.75	17.25	.04745	.10476	2	1	47	2.21

	pH	drought	root area	shoot area	root wt	shoot wt	repl	samples	Ht	shoot/root wt. ratio
125	5.5	severe	2.25	15.75	.02921	.13652	2	2	59	4.67
126	5.5	severe	2.00	15.00	.06425	.11185	2	3	56	1.74
127	5.5	severe	2.75	1.75	.04338	.04664	3	1	35	1.08
128	5.5	severe	5.50	13.50	.07529	.09664	3	2	7	1.28
129	5.5	severe	4.75	10.00	.07909	.09615	3	3	65	1.22
130	5.5	severe	9.00	16.50	.07622	.12658	4	1	62	1.66
131	5.5	severe	5.25	11.00	.05837	.07547	4	2	57	1.29
132	5.5	severe	6.75	22.25	.05987	.13967	4	3	59	2.33
133	5.5	severe	1.75	9.00	.01981	.05344	1	1	62	2.70
134	5.5	severe	1.75	16.75	.01786	.10742	1	2	60	6.01
135	5.5	severe	1.25	7.25	.00927	.04041	1	3	52	4.36
136	5.5	severe	1.50	14.00	.02407	.08020	2	1	52	3.33
137	5.5	severe	4.00	23.00	.05184	.16638	2	2	56	3.21
138	5.5	severe	4.25	19.75	.07684	.13368	2	3	53	1.74
139	5.5	severe	9.50	26.75	.11645	.17501	3	1	55	1.50
140	5.5	severe	7.75	23.00	.11326	.16162	3	2	57	1.43
141	5.5	severe	3.50	15.50	.04860	.08774	3	3	55	1.81
142	5.5	severe	.50	3.75	.00996	.08593	4	1	35	8.63
143	5.5	severe	1.50	6.25	.01510	.12994	4	2	30	8.61
144	5.5	severe	1.50	11.00	.01419	.03889	4	3	38	2.74
145	4.5	control	3.50	18.75	.03758	.10382	1	1	67	2.76
146	4.5	control	2.00	11.25	.03419	.06827	1	2	35	2.00
147	4.5	control	4.25	9.50	.03722	.06499	1	3	47	1.75
148	4.5	control	2.50	11.25	.05509	.10609	2	1	45	1.93
149	4.5	control	7.00	12.00	.06806	.08229	2	2	36	1.21
150	4.5	control	8.00	21.75	.12015	.12517	2	3	40	1.04
151	4.5	control	5.00	9.50	.04442	.05064	3	1	43	1.14
152	4.5	control	6.25	19.75	.06903	.11624	3	2	69	1.68
153	4.5	control	5.00	12.50	.05684	.07637	3	3	46	1.34
154	4.5	control	4.25	11.25	.06503	.07776	4	1	55	1.20
155	4.5	control	.25	3.00	.00460	.04035	4	2	34	8.77
156	4.5	control	2.25	3.75	.03036	.05788	4	3	35	1.91
157	4.5	control	.25	4.00	.00490	.02173	1	1	47	4.43
158	4.5	control	1.75	28.75	.03790	.06614	1	2	75	1.75
159	4.5	control	.75	11.25	.01672	.12499	1	3	50	7.48
160	4.5	control	6.25	16.25	.11142	.11502	2	1	47	1.03
161	4.5	control	4.50	15.00	.06376	.12227	2	2	60	1.92
162	4.5	control	3.00	16.75	.03311	.08491	2	3	52	2.56
163	4.5	control	2.00	9.00	.02743	.05553	3	1	47	2.02
164	4.5	control	1.00	3.75	.01833	.04083	3	2	62	2.23
165	4.5	control	8.00	17.25	.06360	.11014	3	3	60	1.73
166	4.5	control	7.00	14.50	.09448	.09841	4	1	40	1.04
167	4.5	control	7.50	17.50	.01385	.10665	4	2	53	7.70
168	4.5	control	8.00	16.00	.12809	.09499	4	3	38	.74
169	4.5	control	3.00	15.50	.03258	.08523	1	1	60	2.62
170	4.5	control	2.00	9.25	.01584	.04681	1	2	55	2.96
171	4.5	control	4.25	25.25	.03904	.13295	1	3	55	3.41
172	4.5	control	6.25	19.00	.09040	.12142	2	1	42	1.34
173	4.5	control	2.50	22.00	.05854	.15222	2	2	48	2.60
174	4.5	control	3.50	20.00	.04276	.12462	2	3	54	2.91
175	4.5	control	2.50	11.25	.04135	.08175	3	1	47	1.98
176	4.5	control	4.50	8.75	.05682	.05864	3	2	45	1.03
177	4.5	control	6.50	11.75	.09789	.08165	3	3	47	.83
178	4.5	control	6.50	11.25	.08017	.09136	4	1	44	1.14
179	4.5	control	7.00	17.25	.09842	.13078	4	2	62	1.33
180	4.5	control	4.25	10.00	.04278	.06571	4	3	22	1.54
181	4.5	control	2.75	14.25	.02229	.06670	1	1	55	2.99
182	4.5	control	3.50	13.25	.03066	.07384	1	2	57	2.41
183	4.5	control	4.00	21.00	.03533	.13699	1	3	65	3.88
184	4.5	control	1.00	11.25	.01740	.06876	2	1	48	3.95
185	4.5	control	8.75	26.00	.10609	.19324	2	2	63	1.82
186	4.5	control	6.75	18.00	.11724	.11282	2	3	44	.96

	pH	drought	root area	shoot area	root wt	shoot wt	repl	samples	Ht	shoot/root wt. ratio
187	4.5	control	6.25	13.00	.10261	.09215	3	1	55	.90
188	4.5	control	6.75	13.25	.09512	.10570	3	2	55	1.11
189	4.5	control	7.00	22.25	.09580	.14043	3	3	45	1.47
190	4.5	control	.75	12.00	.04139	.08573	4	1	37	2.07
191	4.5	control	5.50	10.75	.09669	.08622	4	2	50	.89
192	4.5	control	4.50	13.50	.05812	.08551	4	3	51	1.47
193	4.5	intermediate	.50	8.50	.01232	.05300	1	1	45	4.30
194	4.5	intermediate	.50	13.75	.01746	.09271	1	2	55	5.31
195	4.5	intermediate	3.50	27.00	.05550	.16864	1	3	52	3.04
196	4.5	intermediate	5.00	17.50	.07253	.11098	2	1	57	1.53
197	4.5	intermediate	5.75	15.50	.06781	.10524	2	2	48	1.55
198	4.5	intermediate	8.00	15.75	.11724	.10891	2	3	62	.93
199	4.5	intermediate	8.50	18.00	.10767	.10194	3	1	52	.95
200	4.5	intermediate	8.00	14.75	.08770	.09653	3	2	55	1.10
201	4.5	intermediate	3.50	9.75	.03235	.06279	3	3	53	1.94
202	4.5	intermediate	3.75	13.25	.03353	.08822	4	1	56	2.63
203	4.5	intermediate	4.00	15.00	.04851	.08992	4	2	51	1.85
204	4.5	intermediate	5.00	21.25	.08562	.13364	4	3	49	1.56
205	4.5	intermediate	1.75	21.75	.03138	.11915	1	1	55	3.80
206	4.5	intermediate	1.75	10.00	.02647	.05443	1	2	50	2.06
207	4.5	intermediate	5.75	22.25	.08017	.15665	1	3	60	1.95
208	4.5	intermediate	9.25	22.50	.14926	.16904	2	1	68	1.13
209	4.5	intermediate	7.25	21.00	.08427	.13981	2	2	49	1.66
210	4.5	intermediate	7.00	14.75	.11158	.11661	2	3	62	1.05
211	4.5	intermediate	4.50	12.25	.06679	.10117	3	1	70	1.51
212	4.5	intermediate	4.50	10.25	.07974	.07639	3	2	39	.96
213	4.5	intermediate	5.75	17.75	.07321	.11137	3	3	52	1.52
214	4.5	intermediate	3.50	7.25	.04376	.05687	4	1	43	1.30
215	4.5	intermediate	3.50	13.00	.03527	.07349	4	2	37	2.08
216	4.5	intermediate	.25	4.25	.00653	.02086	4	3	12	3.19
217	4.5	intermediate	2.00	7.25	.01939	.06123	1	1	50	3.16
218	4.5	intermediate	3.00	19.75	.03564	.10162	1	2	55	2.85
219	4.5	intermediate	4.50	27.50	.06652	.15782	1	3	67	2.37
220	4.5	intermediate	5.25	18.75	.07707	.12904	2	1	51	1.67
221	4.5	intermediate	5.00	14.25	.07909	.09579	2	2	38	1.21
222	4.5	intermediate	6.75	27.75	.10526	.19728	2	3	59	1.87
223	4.5	intermediate	2.25	12.00	.02595	.09401	3	1	50	3.62
224	4.5	intermediate	3.25	10.50	.05489	.07947	3	2	45	1.45
225	4.5	intermediate	3.00	11.75	.03176	.07011	3	3	47	2.21
226	4.5	intermediate	8.00	23.75	.12692	.14079	4	1	38	1.11
227	4.5	intermediate	1.25	7.00	.00952	.03266	4	2	33	3.43
228	4.5	intermediate	8.00	21.25	.11159	.15730	4	3	33	1.41
229	4.5	intermediate	.75	2.00	.01225	.02220	1	1	40	1.81
230	4.5	intermediate	4.00	3.50	.06518	.22411	1	2	70	3.44
231	4.5	intermediate	3.00	18.50	.05503	.10973	1	3	42	1.99
232	4.5	intermediate	4.00	15.50	.04834	.11496	2	1	52	2.38
233	4.5	intermediate	8.00	14.50	.12688	.10785	2	2	37	.85
234	4.5	intermediate	9.50	18.50	.11913	.12722	2	3	41	1.07
235	4.5	intermediate	6.50	23.00	.05747	.16408	3	1	57	2.86
236	4.5	intermediate	2.50	13.00	.02295	.09381	3	2	60	4.09
237	4.5	intermediate	2.75	14.25	.04016	.11769	3	3	60	2.93
238	4.5	intermediate	6.00	11.00	.07317	.08228	4	1	51	1.12
239	4.5	intermediate	3.50	7.00	.03836	.05298	4	2	40	1.38
240	4.5	intermediate	5.75	10.75	.08356	.07589	4	3	52	.91
241	4.5	severe	3.00	28.50	.04015	.13289	1	1	75	3.31
242	4.5	severe	1.00	8.00	.01107	.04917	1	2	45	4.44
243	4.5	severe	.25	5.75	.01088	.03600	1	3	47	3.31
244	4.5	severe	3.25	10.75	.03219	.07139	2	1	25	2.22
245	4.5	severe	3.00	8.00	.03865	.06850	2	2	18	1.77
246	4.5	severe	9.75	30.75	.18002	.17117	2	3	47	.95
247	4.5	severe	2.25	4.50	.03282	.04116	3	1	32	1.25
248	4.5	severe	6.50	12.75	.06519	.09434	3	2	55	1.45

	pH	drought	root area	shoot area	root wt	shoot wt	repl	samples	Ht	shoot/root wt. ratio
249	4.5	severe	3.00	11.75	.03675	.07675	3	3	47	2.09
250	4.5	severe	2.00	11.00	.01273	.06004	4	1	54	4.72
251	4.5	severe	2.25	7.00	.02422	.03547	4	2	34	1.46
252	4.5	severe	5.75	18.00	.06175	.11955	4	3	56	1.94
253	4.5	severe	2.00	13.25	.02949	.08915	1	1	60	3.02
254	4.5	severe	5.00	12.75	.05147	.10139	1	2	65	1.97
255	4.5	severe	4.00	19.50	.05395	.11705	1	3	62	2.17
256	4.5	severe	3.00	14.00	.08760	.09503	2	1	37	1.08
257	4.5	severe	2.00	15.00	.03615	.10631	2	2	66	2.94
258	4.5	severe	5.25	14.00	.08217	.09028	2	3	45	1.10
259	4.5	severe	4.25	12.00	.05805	.09162	3	1	52	1.58
260	4.5	severe	4.75	11.00	.08137	.08547	3	2	6	1.05
261	4.5	severe	5.00	13.50	.07227	.08673	3	3	50	1.20
262	4.5	severe	.75	2.75	.01369	.02111	4	1	20	1.54
263	4.5	severe	4.00	9.25	.05099	.07282	4	2	44	1.43
264	4.5	severe	4.50	12.25	.06982	.08714	4	3	48	1.25
265	4.5	severe	1.00	13.50	.01977	.09183	1	1	55	4.64
266	4.5	severe	.75	10.50	.02430	.06588	1	2	50	2.71
267	4.5	severe	4.00	17.50	.05153	.11888	1	3	55	2.31
268	4.5	severe	4.00	24.00	.04748	.16062	2	1	62	3.38
269	4.5	severe	7.75	25.00	.12447	.15024	2	2	59	1.21
270	4.5	severe	10.00	24.00	.13173	.15170	2	3	53	1.15
271	4.5	severe	6.25	19.00	.08351	.11202	3	1	55	1.34
272	4.5	severe	3.25	8.75	.03650	.05574	3	2	45	1.53
273	4.5	severe	8.00	19.00	.08835	.11439	3	3	62	1.29
274	4.5	severe	8.00	16.00	.13529	.11315	4	1	52	.84
275	4.5	severe	8.00	20.25	.11956	.14602	4	2	55	1.22
276	4.5	severe	4.50	11.50	.04878	.07171	4	3	28	1.47
277	4.5	severe	2.50	19.75	.02568	.12678	1	1	70	4.94
278	4.5	severe	2.00	12.25	.02585	.08384	1	2	55	3.24
279	4.5	severe	3.25	22.50	.02797	.12461	1	3	62	4.46
280	4.5	severe	6.75	25.00	.12244	.13667	2	1	39	1.12
281	4.5	severe	3.50	13.00	.04570	.08104	2	2	45	1.77
282	4.5	severe	2.50	9.75	.04239	.07263	2	3	39	1.71
283	4.5	severe	3.00	13.00	.04199	.08946	3	1	65	2.13
284	4.5	severe	4.25	18.00	.07009	.11752	3	2	47	1.68
285	4.5	severe	5.50	25.00	.05739	.16161	3	3	70	2.82
286	4.5	severe	.25	2.00	.00255	.01887	4	1	13	7.40
287	4.5	severe	2.25	16.25	.01876	.09198	4	2	56	4.90
288	4.5	severe	2.75	11.00	.02713	.06123	4	3	60	2.26
289	3.5	control	1.00	8.00	.01634	.04259	1	1	37	2.61
290	3.5	control	2.00	24.25	.03032	.13413	1	2	52	4.42
291	3.5	control	3.00	21.25	.05580	.15642	1	3	65	2.80
292	3.5	control	7.00	14.00	.08382	.18485	2	1	55	2.21
293	3.5	control	4.25	16.75	.04794	.10212	2	2	72	2.13
294	3.5	control	5.00	25.00	.07977	.09958	2	3	53	1.25
295	3.5	control	3.00	8.00	.05065	.05788	3	1	45	1.14
296	3.5	control	1.50	8.00	.02363	.06758	3	2	42	2.86
297	3.5	control	3.00	9.00	.04128	.07631	3	3	57	1.85
298	3.5	control	1.25	5.00	.02317	.03971	4	1	42	1.71
299	3.5	control	.50	13.00	.00937	.05561	4	2	63	5.93
300	3.5	control	3.25	7.75	.03313	.06902	4	3	48	2.08
301	3.5	control	2.50	14.75	.03806	.10526	1	1	60	2.77
302	3.5	control	3.75	26.00	.06426	.16364	1	2	60	2.55
303	3.5	control	3.50	28.00	.02332	.12599	1	3	57	5.40
304	3.5	control	2.00	8.75	.04235	.08279	2	1	41	1.95
305	3.5	control	4.75	16.25	.05769	.10766	2	2	64	1.87
306	3.5	control	7.00	20.00	.11791	.12175	2	3	48	1.03
307	3.5	control	2.25	6.50	.04468	.06610	3	1	47	1.48
308	3.5	control	4.50	10.50	.08072	.06497	3	2	30	.80
309	3.5	control	5.50	13.00	.08373	.10636	3	3	57	1.27
310	3.5	control	5.25	14.75	.08384	.08605	4	1	38	1.03

	pH	drought	root area	shoot area	root wt	shoot wt	repl	samples	Ht	shoot/root wt. ratio
311	3.5	control	2.50	8.00	.02929	.05147	4	2	42	1.76
312	3.5	control	3.75	11.75	.04432	.07553	4	3	40	1.70
313	3.5	control	2.50	18.25	.03605	.09956	1	1	60	2.76
314	3.5	control	4.00	15.00	.04959	.09205	1	2	60	1.86
315	3.5	control	6.75	17.00	.06374	.10948	1	3	55	1.72
316	3.5	control	6.00	21.00	.09683	.01395	2	1	58	.14
317	3.5	control	3.75	11.75	.02990	.07788	2	2	56	2.60
318	3.5	control	3.25	10.25	.04260	.06845	2	3	45	1.61
319	3.5	control	2.25	5.25	.04038	.03679	3	1	20	.91
320	3.5	control	4.00	8.00	.03903	.05961	3	2	52	1.53
321	3.5	control	7.00	17.00	.10424	.13528	3	3	52	1.30
322	3.5	control	11.50	26.00	.20624	.20198	4	1	55	.98
323	3.5	control	3.75	8.50	.04383	.06095	4	2	52	1.39
324	3.5	control	5.50	19.50	.08758	.14332	4	3	63	1.64
325	3.5	control	.75	19.25	.01559	.12487	1	1	62	8.01
326	3.5	control	1.00	10.75	.01594	.06453	1	2	60	4.05
327	3.5	control	3.50	21.75	.04667	.15097	1	3	55	3.23
328	3.5	control	3.00	12.00	.05299	.09802	2	1	34	1.85
329	3.5	control	12.00	24.25	.15899	.17354	2	2	36	1.09
330	3.5	control	3.00	14.00	.04536	.10692	2	3	59	2.36
331	3.5	control	5.00	17.00	.05173	.11015	3	1	55	2.13
332	3.5	control	7.50	26.25	.10636	.20074	3	2	77	1.89
333	3.5	control	1.50	8.25	.02540	.05782	3	3	45	2.28
334	3.5	control	2.00	7.75	.01618	.04554	4	1	36	2.81
335	3.5	control	2.00	12.25	.01342	.04195	4	2	18	3.13
336	3.5	control	.25	1.25	.00491	.01276	4	3	17	2.60
337	3.5	intermediate	.50	3.00	.00502	.02983	1	1	20	5.94
338	3.5	intermediate	3.00	17.75	.03776	.11265	1	2	70	2.98
339	3.5	intermediate	5.25	23.00	.06842	.14221	1	3	75	2.08
340	3.5	intermediate	7.00	27.50	.06267	.19183	2	1	62	3.06
341	3.5	intermediate	7.00	14.50	.06133	.08974	2	2	51	1.46
342	3.5	intermediate	3.25	25.25	.04960	.15424	2	3	49	3.11
343	3.5	intermediate	3.25	6.25	.03696	.05137	3	1	50	1.39
344	3.5	intermediate	2.00	9.50	.02678	.06621	3	2	47	2.47
345	3.5	intermediate	3.25	13.50	.06571	.07978	3	3	50	1.21
346	3.5	intermediate	4.50	23.00	.05199	.12652	4	1	74	2.43
347	3.5	intermediate	5.00	11.00	.07612	.08060	4	2	39	1.06
348	3.5	intermediate	4.00	16.75	.05070	.11394	4	3	55	2.25
349	3.5	intermediate	.75	8.50	.01646	.06420	1	1	47	3.90
350	3.5	intermediate	2.50	22.25	.03320	.13042	1	2	62	3.93
351	3.5	intermediate	2.00	19.50	.02517	.11862	1	3	60	4.71
352	3.5	intermediate	10.50	20.25	.15091	.13948	2	1	49	.92
353	3.5	intermediate	5.75	16.25	.07846	.11284	2	2	40	1.44
354	3.5	intermediate	5.75	21.75	.09456	.14734	2	3	49	1.56
355	3.5	intermediate	4.75	14.00	.08077	.10304	3	1	55	1.28
356	3.5	intermediate	8.00	11.00	.03923	.07503	3	2	45	1.91
357	3.5	intermediate	2.50	8.00	.04722	.05729	3	3	55	1.21
358	3.5	intermediate	.25	3.00	.01477	.04396	4	1	22	2.98
359	3.5	intermediate	.25	1.25	.01066	.01672	4	2	29	1.57
360	3.5	intermediate	1.75	6.00	.02850	.06005	4	3	37	2.11
361	3.5	intermediate	3.25	13.00	.03211	.06894	1	1	60	2.15
362	3.5	intermediate	2.50	13.00	.02983	.09942	1	2	50	3.33
363	3.5	intermediate	5.75	25.50	.07660	.17179	1	3	80	2.24
364	3.5	intermediate	2.00	11.50	.02745	.07286	2	1	58	2.65
365	3.5	intermediate	7.00	22.50	.07698	.14196	2	2	40	1.84
366	3.5	intermediate	9.00	16.25	.10945	.12278	2	3	57	1.12
367	3.5	intermediate	2.00	7.25	.03334	.05647	3	1	40	1.69
368	3.5	intermediate	4.00	15.50	.05997	.13847	3	2	52	2.31
369	3.5	intermediate	1.75	12.75	.02740	.07906	3	3	62	2.89
370	3.5	intermediate	7.75	18.25	.12125	.13398	4	1	55	1.10
371	3.5	intermediate	1.00	7.50	.02096	.04673	4	2	30	2.23
372	3.5	intermediate	4.00	24.50	.06572	.17464	4	3	60	2.66

	pH	drought	root area	shoot area	root wt	shoot wt	repl	samples	Ht	shoot/root wt. ratio
373	3.5	intermediate	1.75	10.00	.03016	.06573	1	1	55	2.18
374	3.5	intermediate	2.50	9.75	.03116	.06607	1	2	55	2.12
375	3.5	intermediate	2.25	11.00	.02561	.07055	1	3	50	2.75
376	3.5	intermediate	8.00	26.00	.11389	.19783	2	1	65	1.74
377	3.5	intermediate	6.00	25.25	.15189	.17893	2	2	40	1.18
378	3.5	intermediate	5.25	25.00	.09949	.16226	2	3	63	1.63
379	3.5	intermediate	5.25	18.75	.05623	.11614	3	1	45	2.07
380	3.5	intermediate	6.25	18.75	.07188	.12393	3	2	60	1.72
381	3.5	intermediate	3.00	12.50	.02909	.07673	3	3	65	2.64
382	3.5	intermediate	10.00	18.50	.15013	.13766	4	1	52	.92
383	3.5	intermediate	6.50	10.75	.06202	.08719	4	2	52	1.41
384	3.5	intermediate	6.75	16.50	.10591	.11667	4	3	28	1.10
385	3.5	severe	1.75	16.00	.02210	.09759	1	1	52	4.42
386	3.5	severe	.75	9.00	.01188	.05515	1	2	40	4.64
387	3.5	severe	3.50	18.50	.05037	.10889	1	3	42	2.16
388	3.5	severe	3.50	11.00	.04262	.06584	2	1	70	1.54
389	3.5	severe	5.25	18.25	.09613	.15066	2	2	64	1.57
390	3.5	severe	7.25	12.00	.09992	.10882	2	3	48	1.09
391	3.5	severe	1.00	9.50	.00788	.03256	3	1	37	4.13
392	3.5	severe	2.00	4.25	.02124	.03696	3	2	30	1.74
393	3.5	severe	4.25	16.75	.04450	.07922	3	3	45	1.78
394	3.5	severe	10.00	14.00	.12237	.10680	4	1	58	.87
395	3.5	severe	11.00	16.25	.13477	.12755	4	2	52	.95
396	3.5	severe	13.00	27.00	.22304	.18059	4	3	47	.81
397	3.5	severe	2.00	25.25	.02425	.09412	1	1	50	3.88
398	3.5	severe	4.00	26.50	.08113	.16367	1	2	625	2.02
399	3.5	severe	1.50	18.50	.02653	.12267	1	3	475	4.62
400	3.5	severe	.50	20.50	.00958	.12251	2	1	57	12.79
401	3.5	severe	4.00	24.25	.05641	.17742	2	2	57	3.15
402	3.5	severe	7.75	18.25	.09843	.11372	2	3	43	1.16
403	3.5	severe	4.50	15.25	.07316	.13067	3	1	60	1.79
404	3.5	severe	7.00	23.00	.08637	.14723	3	2	50	1.70
405	3.5	severe	3.25	14.50	.04127	.09429	3	3	65	2.28
406	3.5	severe	3.00	10.00	.04608	.06980	4	1	45	1.51
407	3.5	severe	4.00	13.00	.04970	.06703	4	2	41	1.35
408	3.5	severe	1.50	8.00	.02490	.05267	4	3	44	2.12
409	3.5	severe	4.00	31.50	.04342	.13223	1	1	50	3.05
410	3.5	severe	6.25	20.00	.08129	.12401	1	2	55	1.53
411	3.5	severe	6.25	19.75	.06172	.12279	1	3	65	1.99
412	3.5	severe	9.00	16.50	.09314	.09718	2	1	59	1.04
413	3.5	severe	4.50	16.00	.06231	.10888	2	2	42	1.75
414	3.5	severe	8.00	15.00	.08700	.09957	2	3	49	1.14
415	3.5	severe	5.25	19.75	.04613	.08623	3	1	52	1.87
416	3.5	severe	4.25	9.50	.05665	.07142	3	2	42	1.26
417	3.5	severe	5.25	10.50	.04688	.06039	3	3	45	1.29
418	3.5	severe	.25	4.00	.01067	.06122	4	1	25	5.74
419	3.5	severe	1.25	5.75	.01345	.06131	4	2	40	4.56
420	3.5	severe	6.25	14.75	.06539	.09312	4	3	52	1.42
421	3.5	severe	3.00	10.25	.02637	.06049	1	1	47	2.29
422	3.5	severe	6.00	24.25	.05771	.15074	1	2	65	2.61
423	3.5	severe	6.00	19.50	.07932	.13022	1	3	35	1.64
424	3.5	severe	2.00	15.25	.04574	.09536	2	1	48	2.08
425	3.5	severe	4.50	16.25	.07407	.10286	2	2	49	1.39
426	3.5	severe	9.75	22.25	.13297	.15520	2	3	40	1.17
427	3.5	severe	4.00	15.25	.05295	.09205	3	1	55	1.74
428	3.5	severe	2.50	9.50	.03053	.07296	3	2	50	2.39
429	3.5	severe	2.75	11.75	.04702	.07518	3	3	45	1.60
430	3.5	severe	1.25	4.75	.02570	.04000	4	1	32	1.56
431	3.5	severe	7.50	21.50	.12438	.16534	4	2	42	1.33
432	3.5	severe	8.00	14.50	.12211	.10546	4	3	47	.86

Appendix 6: Solution Culture Experiment--Results

PART a. SUGAR MAPLE 2-YEAR OLDS: GROWTH DATA AND ELEMENT CONCENTRATIONS IN ROOTS ,STEMS AND LEAVES.

PART b. WHITE SPRUCE SEEDLINGS: ELEMENT CONCENTRATIONS IN ROOTS, STEMS AND NEEDLES.

PART c. WHITE SPRUCE SEEDLINGS: GROWTH DATA

LEGEND

ALL CONCENTRATIONS IN µg/g

	box#	plant #	PEG (g/L)	Al (mg/L)	pH	# days treated	wet. wt. start (g)	wet. wt. end (g)	chg. ww	% chg. ww/day	root len. st.-cm	root len. end	root len. chg.	overall root growth
1	a=1	a=1	a=0	a=0	a=5.5	14	1.16	1.17	1.00E-2	6.16E-2	10.0	11.0	1.0	some
2	a=1	b=2	a=0	a=0	a=5.5	14	1.31	1.34	3.00E-2	.16	10.0	13.0	3.0	some
3	a=1	c=3	a=0	a=0	a=5.5	14	3.30	2.73	-.57	-1.23	10.0	10.0	0	some
4	b=2	a=1	a=0	a=0	b=4.0	14	2.10	1.91	-.19	-.65	12.5	10.0	-2.5	none
5	b=2	b=2	a=0	a=0	b=4.0	14	2.65	1.95	-.70	-1.89	16.0	13.0	-3.0	a lot
6	b=2	c=3	a=0	a=0	b=4.0	14	3.01	2.30	-.71	-1.68	15.0	15.0	0	some
7	c=3	a=1	a=0	b=50	a=5.5	14	1.29	1.44	.15	.83	10.0	11.0	1.0	a lot
8	c=3	b=2	a=0	b=50	a=5.5	14	1.69	1.82	.13	.55	11.0	12.0	1.0	a lot
9	c=3	c=3	a=0	b=50	a=5.5	14	2.13	1.86	-.27	-.91	10.0	11.0	1.0	none
10	d=4	a=1	a=0	b=50	b=4.0	14	2.25	2.42	.17	.54	13.0	16.0	3.0	a lot
11	d=4	b=2	a=0	b=50	b=4.0	14	2.15	2.12	-3.00E-2	-.10	11.0	10.5	-5.0E-1	some
12	d=4	c=3	a=0	b=50	b=4.0	14	2.68	3.80	1.12	2.99	11.5	12.0	5.0E-1	a lot
13	e=5	a=1	b=25	a=0	a=5.5	14	1.21	1.09	-.12	-.71	10.0	10.0	0	none
14	e=5	b=2	b=25	a=0	a=5.5	14	2.39	2.12	-.27	-.81	10.0	11.5	1.5	none
15	e=5	c=3	b=25	a=0	a=5.5	14	2.40	1.92	-.48	-1.43	10.0	10.5	5.0E-1	a lot
16	f=6	a=1	b=25	a=0	b=4.0	14	2.17	1.99	-.18	-.59	10.0	11.0	1.0	none
17	f=6	b=2	b=25	a=0	b=4.0	14	1.61	1.32	-.29	-1.29	12.5	11.5	-1.0	none
18	f=6	c=3	b=25	a=0	b=4.0	14	2.18	1.89	-.29	-.95	13.5	13.0	-5.0E-1	some
19	g=7	a=1	b=25	b=50	a=5.5	14	2.68	1.99	-.69	-1.84	15.0	16.0	1.0	a lot
20	g=7	b=2	b=25	b=50	a=5.5	14	1.61	1.19	-.42	-1.86	21.0	16.0	-5.0	a lot
21	g=7	c=3	b=25	b=50	a=5.5	14	2.46	2.21	-.25	-.73	10.0	11.5	1.5	a lot
22	h=8	a=1	b=25	b=50	b=4.0	14	1.84	2.09	.25	.97	10.0	10.5	5.0E-1	some
23	h=8	b=2	b=25	b=50	b=4.0	14	2.35	1.95	-.40	-1.22	16.9	19.5	2.6	a lot
24	h=8	c=3	b=25	b=50	b=4.0	14	1.70	2.06	.36	1.51	10.0	12.0	2.0	some

a.

	dry wt. root (mg)	dry wt. stem (mg)	dry wt. leaves (mg)	# leaves start	# leaves end	chg. # leaves	dry wt. total	Al root	Al stem	Al leaves	B root	B stem	B leaves	Ba root
1	117.0	224.5	91.5	2	2	0	433.0	2120	92.7	•	55.4	22.20	52.5	14.400
2	165.0	269.8	74.3	2	2	0	509.1	3190	563.0	•	18.7	74.30	88.3	19.800
3	503.5	474.7	216.4	2	2	0	1194.6	1580	211.0	22.0	27.3	33.60	65.8	11.000
4	271.7	343.0	145.8	4	4	0	760.5	5450	416.0	12.5	32.2	41.10	50.2	14.500
5	160.1	512.3	230.6	4	4	0	903.0	1470	110.0	8.5	40.3	29.00	109.0	11.500
6	428.5	415.7	194.8	4	4	0	1039.0	1060	76.7	•	63.2	5.76	20.1	7.020
7	201.4	190.3	143.9	2	2	0	535.6	3600	528.0	26.6	21.2	89.20	59.8	13.800
8	197.9	380.5	118.5	2	2	0	696.9	2650	92.9	35.1	29.1	25.10	160.0	12.300
9	291.2	376.1	88.4	4	4	0	755.7	3130	530.0	6.5	72.9	35.20	26.8	10.900
10	310.9	464.4	213.7	4	4	0	989.0	2750	347.0	52.0	16.8	28.00	36.6	4.310
11	258.9	456.2	179.1	4	4	0	894.2	2270	221.0	53.1	81.3	29.10	29.1	3.440
12	452.2	726.7	380.8	6	6	0	1559.7	2520	224.0	51.5	20.9	30.90	51.0	3.830
13	178.7	212.3	59.0	3	3	0	450.0	3840	491.0	•	25.4	106.00	90.0	52.900
14	268.8	473.2	107.8	3	4	1	849.8	2230	325.0	65.4	45.8	19.80	21.0	37.400
15	385.3	301.5	176.4	2	2	0	863.2	875	90.2	6.7	43.3	19.50	90.5	27.400
16	277.0	469.1	116.2	4	4	0	862.3	3320	459.0	•	20.6	24.40	52.3	15.900
17	184.6	297.1	90.0	2	2	0	571.7	3610	801.0	•	22.0	108.00	115.0	12.600
18	258.5	487.5	130.7	4	4	0	876.7	1090	271.0	20.4	66.5	21.50	39.5	8.500
19	193.7	416.8	212.7	2	2	0	823.2	1590	103.0	•	32.5	60.40	108.0	7.300
20	132.0	257.1	147.9	2	2	0	537.0	2170	214.0	•	41.7	37.20	67.9	9.680
21	254.0	381.2	161.6	2	2	0	796.8	2970	205.0	15.0	37.8	41.70	99.7	9.880
22	313.6	300.7	148.6	4	4	0	762.9	3170	322.0	42.2	27.4	37.10	104.0	4.920
23	316.2	357.0	137.4	1	1	0	810.6	3240	181.0	•	65.3	51.70	127.0	5.410
24	231.0	389.7	156.6	2	2	0	777.3	6110	357.0	21.6	24.9	9.53	31.5	8.350

	Ba stem	Ba leaves	Ca root	Ca stem	Ca leaves	Cr root	Cr stem	Cr leaves	Cu root	Cu stem	Cu leaves	Fe root	Fe stem	Fe leaves	Mg root	Mg stem	Mg leaves
1	8.510	.856	5250	12100	4950	3.570	.172	.233	69.20	8.73	6.40	1670.0	24.0	•	1540	954	1600
2	10.300	1.130	8210	13900	5230	5.600	.904	•	65.30	5.20	7.08	2410.0	280.0	•	1820	903	962
3	6.370	.975	6450	11900	4550	3.720	.477	1.790	42.80	4.97	6.56	885.0	45.4	•	1170	829	1710
4	8.050	.982	5780	11800	3580	9.190	.083	2.210	85.60	6.42	7.65	4040.0	66.1	14.8	2010	904	1680
5	5.810	2.280	3840	8740	6380	3.040	.157	.217	96.70	6.37	8.27	1340.0	44.0	•	996	559	1760
6	3.970	.715	4290	7760	3860	2.930	.249	1.650	53.70	6.16	15.30	918.0	27.9	•	938	795	1710
7	8.280	1.150	4860	9470	4200	4.990	.721	2.320	44.90	5.81	7.36	2290.0	378.0	•	2000	831	1250
8	6.770	1.480	7260	11700	7270	4.210	•	1.810	49.60	5.82	7.68	1600.0	41.0	21.7	2150	601	1670
9	7.570	.616	7690	11600	5160	4.740	7.000E-3	1.420	38.90	5.27	7.42	2230.0	71.9	•	1500	728	1410
10	7.820	1.020	5520	12900	4350	2.830	.723	2.970	31.30	4.69	7.82	1100.0	118.0	32.8	1240	779	1360
11	6.170	1.280	5720	9560	4090	2.440	.545	2.660	17.80	4.11	5.61	709.0	114.0	203.0	1010	629	1510
12	5.520	1.770	3650	8460	5120	1.760	.293	2.150	26.80	4.95	13.10	668.0	51.4	42.4	768	549	1830
13	7.790	.926	8740	14500	5040	7.370	1.080	.748	56.10	4.40	6.73	3350.0	317.0	•	1920	870	1450
14	7.790	2.380	6480	10800	4150	4.100	.510	4.810	50.80	5.42	11.80	1770.0	83.5	576.0	1660	1050	1270
15	5.920	2.600	8280	10800	4760	1.690	•	1.060	42.20	4.80	13.60	343.0	•	•	1170	904	2010
16	9.230	2.100	6300	12400	5240	7.710	1.360	.761	85.90	4.65	7.48	2870.0	220.0	•	1720	831	1330
17	9.930	.738	3850	13500	4650	7.260	1.830	•	85.90	10.90	9.52	3500.0	327.0	•	1430	941	1500
18	7.420	1.700	6080	10800	4770	4.220	1.360	2.850	78.30	12.10	14.10	606.0	228.0	198.0	1040	748	1530
19	5.870	2.570	3710	8780	6860	2.590	•	.466	77.40	7.66	8.96	805.0	•	•	987	666	2130
20	7.690	1.160	5660	10800	6080	3.520	.575	•	98.10	5.16	6.09	1130.0	134.0	•	1840	1060	2030
21	5.750	.751	5010	8630	3250	6.370	1.200	1.510	75.10	7.01	7.56	1870.0	149.0	•	1590	967	1460
22	7.500	.688	4050	11300	3260	3.370	.635	2.250	29.50	5.17	12.50	1200.0	186.0	•	1280	631	1410
23	5.440	1.820	6970	12500	8860	2.710	•	•	39.90	4.29	9.75	848.0	6.7	•	815	822	1930
24	8.420	1.180	5640	12100	4890	6.300	.874	3.160	42.40	5.15	8.46	2350.0	187.0	•	1630	765	1400

	Mn root	Mn stem	Mn leaves	Ni root	Ni stem	Ni leaves	P root	P stem	P leaves	Pb root	Pb stem	S root	S stem	S leaves	Si root	Si stem	Si leaves	V root	V stem
1	267.0	73.5	5.0	5.420	4.000	.128	1750	762	1600	14.30	.	2190	832	2180	21.8	7.8	23.60	3.85	.1460
2	288.0	166.0	.	6.290	1.580	.	1430	1050	1600	18.50	.	1740	929	2170	284.0	16.1	10.60	6.72	.7190
3	135.0	38.5	82.2	4.260	1.650	1.640	1200	956	1880	12.30	4.20	938	677	1840	47.0	11.3	.	3.62	.0832
4	140.0	5.5	26.0	60.800	.612	2.210	1360	878	2340	21.50	.	1190	842	2600	340.0	19.5	10.80	11.30	.0359
5	161.0	94.1	226.0	46.900	1.030	3.240	2460	1070	1160	39.50	6.74	1910	914	1900	41.0	14.5	5.07	2.79	.0969
6	156.0	69.2	39.6	2.790	.942	.	1820	1110	1610	9.76	18.90	1360	716	1460	66.3	7.4	.23	2.08	.0250
7	543.0	129.0	13.7	9.440	1.710	1.600	1650	1030	1410	15.20	.	1760	846	2150	39.4	49.2	12.00	6.80	.4660
8	369.0	100.0	237.0	5.790	1.290	.	941	516	1750	24.30	5.63	1660	635	2180	38.9	12.9	17.10	4.56	.
9	115.0	52.0	140.0	3.840	1.280	.	1170	771	2750	154.00	6.46	1390	729	2360	31.8	29.0	12.10	5.11	.0140
10	360.0	114.0	219.0	3.860	1.550	3.180	1680	862	1850	13.60	5.07	1540	732	2380	51.0	56.4	7.10	2.70	.4880
11	142.0	138.0	108.0	1.820	1.590	.	1700	970	1640	15.70	3.25	2220	810	2220	70.9	13.3	12.00	2.50	.2370
12	114.0	100.0	251.0	1.880	1.050	2.820	2480	1020	1540	13.30	4.43	1650	664	1970	64.6	16.4	12.20	1.91	.1020
13	319.0	51.4	.	8.980	.824	.190	1130	1110	2420	15.90	.	1410	773	2250	66.2	28.9	24.30	9.47	.5690
14	130.0	119.0	.	5.000	1.500	.	1350	784	3760	12.70	4.37	1450	882	2440	103.0	36.6	38.50	4.89	.3390
15	115.0	2.9	88.7	3.340	.	.	1350	704	2440	9.07	.	1390	646	2470	30.6	10.7	7.39	1.21	.
16	263.0	71.2	107.0	6.260	1.840	2.170	1640	738	2490	19.10	6.53	1580	653	3010	113.0	45.1	4.28	7.01	.8670
17	197.0	147.0	.	5.090	1.920	.	1520	1020	2610	16.80	4.29	1340	917	2670	91.0	24.7	41.90	7.09	1.0100
18	97.2	57.1	112.0	6.270	1.380	.	1560	1060	3510	61.80	13.20	1310	836	2210	49.2	35.5	12.80	1.77	.5010
19	178.0	35.4	.	5.100	.958	2.930	1970	1220	1150	13.90	.	2420	1140	2390	54.8	8.6	10.10	2.55	.
20	169.0	406.0	172.0	6.940	2.000	35.900	2910	1130	1020	20.30	.	2710	938	2350	44.3	19.2	10.70	2.91	.2300
21	145.0	123.0	12.3	27.700	2.550	.	1630	1200	1140	14.70	3.51	1820	864	1750	49.5	17.0	9.36	5.41	.2580
22	208.0	22.9	.	2.600	2.920	2.600	2820	915	2410	11.50	.	2090	743	1860	46.6	18.3	14.30	3.32	.2840
23	236.0	39.9	58.8	3.050	.	2.320	2600	812	3720	14.00	3.75	1600	762	3030	30.0	14.5	4.33	2.32	.
24	182.0	111.0	36.3	4.030	1.660	.	2820	1110	1630	16.30	5.01	1690	707	1740	92.4	20.7	.55	6.50	.4080

	Zn root	Zn stem	Zn leaves
1	88.1	17.7	.
2	87.3	12.7	13.9
3	58.2	15.8	15.0
4	51.0	12.6	.
5	36.6	10.7	20.0
6	21.1	12.3	14.6
7	108.0	23.7	.
8	79.6	10.5	16.1
9	36.9	16.6	20.6
10	30.7	14.3	15.5
11	16.1	8.0	10.1
12	29.4	12.4	16.6
13	112.0	18.4	20.9
14	79.8	14.7	31.6
15	57.3	12.9	23.2
16	42.2	14.8	22.8
17	34.3	22.0	21.4
18	24.9	14.5	19.7
19	43.9	14.6	28.7
20	43.9	13.5	23.6
21	60.7	16.9	18.8
22	17.8	12.8	21.9
23	15.1	10.6	22.2
24	45.5	22.1	18.3

	box#	plant #	PEG (g/L)	Al (mg/L)	pH	# days treated	dry wt. root (g)	dry wt. stem (g)	dry wt. needles (g)	dry wt. total	root Al ppm	stem Al ppm	needle Al ppm	root Ba ppm	stem Ba ppm	needle Ba ppm
1	a-1	a-1	a-0	a-0	a-5.5	21	.377	.323	.689	1.389	560	10.50	53.9	168.0	160.2	160.0
2	a-1	b-2	a-0	a-0	a-5.5	21	.667	.485	.988	2.140	504	12.30	27.3	160.0	114.0	118.0
3	a-1	c-3	a-0	a-0	a-5.5	21	.911	.403	.625	1.939	1840	15.80	77.0	•	132.0	•
4	b-2	a-1	a-0	a-0	b-4.0	21	.327	.555	.830	1.712	1320	9.47	36.0	346.0	180.0	196.0
5	b-2	b-2	a-0	a-0	b-4.0	21	.624	.703	1.122	2.449	631	13.40	34.6	•	•	289.0
6	b-2	c-3	a-0	a-0	b-4.0	21	.814	.493	1.014	2.321	1140	11.90	41.3	•	•	•
7	c-3	a-1	a-0	b-50	a-5.5	21	.312	.421	.817	1.550	1930	12.10	23.0	•	•	•
8	c-3	b-2	a-0	b-50	a-5.5	21	.438	.589	1.199	2.226	1220	14.40	33.9	•	•	•
9	c-3	c-3	a-0	b-50	a-5.5	21	.889	.589	.974	2.452	2700	15.20	39.0	•	117.0	299.0
10	d-4	a-1	a-0	b-50	b-4.0	21	.201	.408	.714	1.323	14600	238.00	203.0	•	194.0	246.0
11	d-4	b-2	a-0	b-50	b-4.0	21	.726	.432	.824	1.982	16800	67.70	67.2	•	•	159.0
12	d-4	c-3	a-0	b-50	b-4.0	21	.881	.501	.951	2.333	10700	•	210.0	•	•	•
13	e-5	a-1	b-120	a-0	a-5.5	13	.242	.216	.697	1.155	530	13.20	39.4	92.1	128.0	192.0
14	e-5	b-2	b-120	a-0	a-5.5	13	.350	.349	.762	1.461	1460	18.60	67.2	158.0	129.0	159.0
15	e-5	c-3	b-120	a-0	a-5.5	13	.780	.412	.704	1.896	1940	10.60	51.1	•	142.0	125.0
16	f-6	a-1	b-120	a-0	b-4.0	13	.229	.240	.558	1.027	452	21.30	80.1	86.2	103.0	139.0
17	f-6	b-2	b-120	a-0	b-4.0	13	.335	.274	.840	1.449	289	17.50	52.7	•	95.1	85.6
18	f-6	c-3	b-120	a-0	b-4.0	13	.444	.358	1.090	1.892	311	17.90	233.0	284.0	116.0	•
19	g-7	a-1	b-120	b-50	a-5.5	13	.302	.199	.456	.957	1050	22.80	49.1	•	206.0	100.0
20	g-7	b-2	b-120	b-50	a-5.5	13	.281	.299	.733	1.313	1070	25.20	43.7	•	99.5	92.1
21	g-7	c-3	b-120	b-50	a-5.5	13	.806	.603	.640	2.049	673	11.50	34.2	157.0	90.8	94.6
22	h-8	a-1	b-120	b-50	b-4.0	13	.195	.197	.454	.846	1760	23.90	430.0	•	118.0	115.0
23	h-8	b-2	b-120	b-50	b-4.0	13	.370	.286	.718	1.374	1570	15.30	37.9	•	123.0	•
24	h-8	c-3	b-120	b-50	b-4.0	13	.526	.335	.728	1.589	990	14.20	39.7	•	115.0	•

b.

	root Ca ppm	stem Ca ppm	needle Ca ppm	root Cl ppm	stem Cl ppm	needle Cl ppm	root Cu ppm	stem Cu ppm	root K ppm	stem K ppm	needle K ppm	root Mg ppm	stem Mg ppm	needle Mg ppm	root Mn ppm
1	10500	5160	12100	250	680	1290	42.2	•	2980	8960	11700	1850	1950	2410	223.0
2	12500	5490	13700	179	1020	1570	57.2	•	•	9110	12600	2440	2310	3240	216.0
3	10200	3500	15200	234	1320	2740	•	•	•	9070	15200	5340	2380	4160	275.0
4	5880	3240	6980	553	1050	1040	135.0	•	•	8450	10100	3140	1130	2940	246.0
5	8480	3110	9770	212	1860	1510	109.0	•	•	13900	8720	2820	1250	1890	240.0
6	11300	3970	9660	179	674	1190	96.0	•	•	8540	13300	4060	1820	2100	285.0
7	9160	1830	7120	1690	5990	4520	•	•	•	5540	6100	4170	895	1250	337.0
8	7720	2120	6990	932	9670	10800	•	•	•	11800	10500	2540	1760	2410	306.0
9	8050	3640	9320	1360	8210	9830	•	•	•	7460	13500	5710	1330	2890	279.0
10	•	3140	7350	3440	7190	6450	175.0	•	•	9760	8130	4760	959	4850	104.0
11	2020	1730	15400	502	8790	1810	•	•	•	5580	12000	3000	1270	2510	33.9
12	2130	2430	10600	2400	5570	4400	•	•	•	9860	7580	6810	2070	3060	77.3
13	9880	5320	13900	168	722	2140	•	•	•	3820	11600	1660	1880	3160	180.0
14	10300	7420	15400	150	326	1810	•	•	•	2580	12000	2950	1550	2510	176.0
15	6610	7410	13400	152	805	1400	•	•	•	6880	9660	4180	2160	2260	173.0
16	7470	4990	12200	414	720	1360	237.0	•	4060	5800	11400	2250	1440	1900	163.0
17	7330	6080	13500	170	733	2120	127.0	•	•	2610	10500	1100	1870	2340	114.0
18	7360	7010	1420	168	603	73	109.0	•	•	4090	•	1500	1960	369	123.0
19	4520	5030	15000	305	2500	2150	•	•	•	6160	8780	1660	3220	3240	93.3
20	9060	5290	15200	297	2690	2740	•	•	•	3690	10200	2440	1730	2560	105.0
21	8290	4090	12800	1090	887	1590	•	6.7	4300	4380	4480	2310	1690	2530	166.0
22	5700	4930	12200	875	5530	5570	76.9	•	•	4480	12500	3690	1740	4040	175.0
23	7270	3390	10400	382	3264	5600	85.1	•	•	•	11700	2970	1200	2530	198.0
24	7190	4300	10800	406	2080	2620	48.8	•	•	3550	8300	2090	2180	2710	153.0

	stem Mn ppm	needle Mn ppm	root Na ppm	stem Na ppm	needle Na ppm	root U ppm	stem U ppm	needle U ppm	root V ppm	stem V ppm	needle V ppm
1	98.6	189.0	333.0	561.0	188.0	•	•	•	5.11	.34	.35
2	64.9	196.0	199.0	882.0	245.0	.48	•	.45	5.28	.22	•
3	49.0	463.0	360.0	836.0	168.0	•	•	•	4.09	.47	•
4	107.0	263.0	533.0	83.9	•	•	.44	2.19	5.29	•	.45
5	121.0	209.0	228.0	•	•	•	.70	1.10	2.43	•	•
6	100.0	229.0	316.0	362.0	•	1.68	.95	1.66	6.57	•	•
7	98.3	188.0	2370.0	4660.0	1550.0	1.07	•	1.89	5.03	•	•
8	46.2	234.0	1970.0	6550.0	6070.0	1.09	.91	1.51	2.37	•	•
9	59.7	220.0	3120.0	5250.0	3390.0	•	.49	1.47	4.67	•	•
10	87.5	203.0	1800.0	2160.0	1650.0	•	•	•	•	•	•
11	83.8	302.0	257.0	4080.0	424.0	•	•	.39	1.89	•	•
12	88.7	208.0	1890.0	176.0	•	•	•	•	4.21	•	•
13	80.4	400.0	842.0	1710.0	444.0	.79	.32	.48	3.93	•	•
14	49.0	302.0	809.0	1490.0	424.0	•	.18	.39	9.06	•	•
15	51.9	268.0	775.0	739.0	84.7	1.01	.12	•	6.02	•	•
16	108.0	287.0	1570.0	2100.0	1500.0	.59	.23	.34	4.94	•	.65
17	66.8	233.0	708.0	2500.0	518.0	•	•	•	3.35	•	•
18	66.9	22.6	555.0	2330.0	237.0	.41	•	.40	4.72	•	1.09
19	77.2	236.0	994.0	3020.0	549.0	1.79	.67	•	4.59	•	•
20	35.2	250.0	1170.0	3720.0	789.0	•	•	•	5.27	•	•
21	88.4	286.0	2470.0	159.0	•	•	•	.30	5.34	•	•
22	77.3	331.0	1440.0	4430.0	2530.0	•	.27	•	7.56	•	•
23	43.4	189.0	1120.0	3270.0	2120.0	1.09	.45	•	7.83	•	•
24	54.2	286.0	1130.0	2090.0	288.0	•	.80	2.61	5.54	•	•

C.

	box#	plant #	PEG (g/L)	Al (mg/L)	pH	# days treated	wet. wt. start (g)	wet. wt. end (g)	chg. ww	% chg. ww/day
1	a=1	a=1	a=0	a=0	a=5.5	21	6.07	5.41	-.66	-.52
2	a=1	b=2	a=0	a=0	a=5.5	21	8.84	9.04	.20	.11
3	a=1	c=3	a=0	a=0	a=5.5	21	10.79	9.73	-1.06	-.47
4	b=2	a=1	a=0	a=0	b=4.0	21	5.37	5.55	.18	.16
5	b=2	b=2	a=0	a=0	b=4.0	21	8.72	7.89	-.83	-.45
6	b=2	c=3	a=0	a=0	b=4.0	21	9.86	8.65	-1.21	-.58
7	c=3	a=1	a=0	b=50	a=5.5	21	4.88	5.22	.34	.33
8	c=3	b=2	a=0	b=50	a=5.5	21	8.44	6.95	-1.49	-.84
9	c=3	c=3	a=0	b=50	a=5.5	21	9.39	10.08	.69	.35
10	d=4	a=1	a=0	b=50	b=4.0	21	3.80	3.99	.19	.24
11	d=4	b=2	a=0	b=50	b=4.0	21	7.17	7.24	7.00E-2	4.65E-2
12	d=4	c=3	a=0	b=50	b=4.0	21	9.07	9.04	-3.00E-2	-1.58E-2
13	e=5	a=1	b=120	a=0	a=5.5	13	4.45	2.61	-1.84	-3.18
14	e=5	b=2	b=120	a=0	a=5.5	13	5.49	2.97	-2.52	-3.53
15	e=5	c=3	b=120	a=0	a=5.5	13	8.06	4.75	-3.31	-3.16
16	f=6	a=1	b=120	a=0	b=4.0	13	5.30	2.91	-2.39	-3.47
17	f=6	b=2	b=120	a=0	b=4.0	13	5.44	3.77	-1.67	-2.36
18	f=6	c=3	b=120	a=0	b=4.0	13	7.34	5.00	-2.34	-2.45
19	g=7	a=1	b=120	b=50	a=5.5	13	3.73	1.96	-1.77	-3.65
20	g=7	b=2	b=120	b=50	a=5.5	13	4.09	3.50	-.59	-1.11
21	g=7	c=3	b=120	b=50	a=5.5	13	7.12	6.05	-1.07	-1.16
22	h=8	a=1	b=120	b=50	b=4.0	13	3.68	2.46	-1.22	-2.55
23	h=8	b=2	b=120	b=50	b=4.0	13	4.84	3.46	-1.38	-2.19
24	h=8	c=3	b=120	b=50	b=4.0	13	6.64	4.27	-2.37	-2.75

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Effect of drought, aluminum, and
low pH on growth and chemical
composition of sugar maple
seedlings : R. A. C. project no.
78234